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Specification and Guidelines for the use of specialist products for **Mechanised Tunnelling (TBM)** in Soft Ground and Hard Rock

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FOREWORD

EFNARC is the European federation dedicated to specialist construction chemicals and concrete systems. It was founded in March 1989 by five national trade associations representing producers and applicators of specialty construction products. Membership has since been widened to include major European companies who have no national body or institution to represent their interests. EFNARC provides a common voice for the specialist construction industry to make known its comments and views to the European Commission, CEN Technical Committees and other groups dealing with European Harmonisation of Specifications and Standards. Its Members are active in all European countries.

EFNARC has achieved an excellent international reputation for its work in preparing authoritative Specifications and Guidelines for Sprayed Concrete, Industrial Flooring, Soft Ground Tunnelling and Self Compacting Concrete. Already, these new Specifications have achieved acceptance internationally reflecting the wide scope of technical expertise of EFNARC members.

The mechanised tunnelling (TBM) Technical Committee was formed at the end of 1998. Its mission was to establish the first European Specification for specialist products used in association with the TBM in soft ground tunnel construction. This tunnelling technology has been increasingly used, but until now not regulated by any national or international standard. Experts in all aspects of tunnelling technology participated in the technical committee to realise this project and the guidelines were finally published in November 2001.

In January 2004, the TBM technical committee met to review the 2001 guidelines and agreed to update them on the basis of new technology and requirements. It was also agreed that the guidelines should be extended to cover Hard Rock TBM and additional committee members were sought with specific expertise in this area.

This document replaces the earlier guidelines on Soft Ground Tunnelling and its format has been changed to into 3 parts covering; common requirements for TBM, information on the use of specialty products for soft ground and information on the use of specialty products for hard rock. It includes aspects of mechanised tunnelling technology relevant to specialist construction chemicals suppliers, contractors, consultants, specifiers and tunnel boring machine manufacturers.

EFNARC recognises that all specifications must be living documents able to be refined and extended in the light of practical experience and future developments. The information and guidance presented is given as best practice based on the experience of EFNARC TC members but it is recognised that it may not be fully representative of the wider tunnelling industry. Comments on this specification are therefore invited and should be sent to EFNARC at the address shown on the cover page.

Acknowledgements

EFNARC wishes to acknowledge gratefully all the contributions and comments made by members of its TBM Technical Committee and also by individual experts.

CONTENTS

This document comprises Guidelines on the use of specialist products in soft ground and hard rock tunnelling and also Specification clauses for certain of those products. These Specification clauses can be identified by the grey shading of the tables in which the requirements are listed.

1. Scope

This document provides Specifications and Guidelines dealing with specialist products and applications used in mechanised tunnelling, in association with Tunnel Boring Machines (TBM) of the following types:

- Slurry Shield Machines
- Earth Pressure Balanced Machine (EPBM)
- Hard Rock TBM

Products and applications concerning structural linings, concrete segments, repairs, injection and water-proofing membranes are not included in the scope of the present document.

This document contains the following three parts:

Part 1: General

- Referenced Standards
- Definitions
- Geotechnical Considerations
- Declaration of Conformity
- Quality Control
- Marking and Labelling
- Environment - Health and Safety

Part 2: Soft Ground

Product categories included:

- soil conditioners
- slurry materials and additives
- annulus back-grouting mortars
- tail seal compounds

Part 3: Hard Rock

- Product categories included:
- Anti wear additives
- Dust control

Part 1: General

2. Referenced Standards

EN 197-1	Cement - composition, specification and conformity criteria
EN 413	Masonry cement
EN 480	Admixtures for concrete, mortar or grout - test methods
EN 934	Admixtures for concrete, mortar or grout
EN 1377	Cone penetrometer test
EN 12350-2	Testing fresh concrete: Part 2: Slump test
EN 12620	Aggregates for concrete
EN ISO 13500	Drilling Fluids
ASTM C230	Flowtable for use in tests of hydraulic cement
ASTM D2938	Unconfined Compressive Strength of Intact Rock Core Specimens
ASTM D3967	Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens

3. Definitions

For the purposes of this specification the following definitions apply:

- Annular Space

  Void between the external part of the lining and the ground.
- Annulus Grouting

  Injection to fill the annular space.
- Confinement

  The result of the application of a pressure to the front to keep the ground at given conditions of stability and deformation.
- Cutter Head

  The turning part at the front of the TBM which supports the cutting tools.
- Disc Cutter

  The cutting tool used for hard rock excavation.
- Earth Pressure Balanced Machines (EPBM)

  Closed shield TBM with active face support by the pressurised soil.
- Foam

  Soil conditioning material made from a foaming solution and air.
- Foaming Agent Concentration (CF)

  Percentage ratio between the weight of the surface-active agents used and the total weight of the foaming solution.
- Foam Expansion Ratio (FER)

  Ratio between the volume of the foam at working pressure and the volume of foaming solution used.
- Foam Injection Ratio (FIR)

  Ratio between the volume of foam injected at working pressure and the volume of the ground in place.

- Foaming Solution

  Mixture of water and surfactant.

- Muck

  Mixture of excavated ground or rocks with or without any conditioning agent (EPBM method).

- Segments/Tubbing

  Precast elements set up to form the tunnel lining (They may be of concrete, steel, cast iron or ductile cast iron).

- Shield

  Shelter system, made by a metallic structure, to protect the working area.

- Slurry

  Viscous suspension of mineral and/or polymeric products.

- Slurry Shield Machine

  Closed shield TBM with active face support by the pressurised slurry.

- Mud Cake

  Fine membrane of dewatered slurry in or at the surface of the soil to stabilise the excavation.

- Tail Seal

  Flexible material/barrier to prevent water or grout ingress between the lining and the shield.

- TBM (Tunnel Boring Machine)

  Machines designed to create bored tunnels. They perform several functions, from the excavation only to the application of the final lining.

- Working Chamber

The pressurised area of the TBM immediately behind the cutting head and in front of the bulkhead.

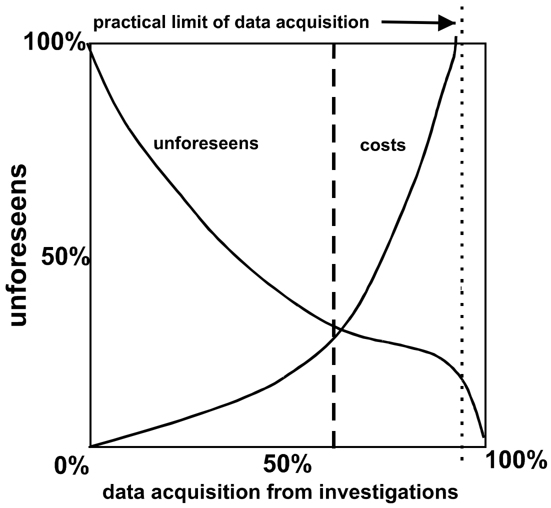
Note:

General definitions relating to tunnelling are available in the multi-lingual glossary issued by AFTES (Association Française des Travaux en Souterrain).

4. Geotechnical Considerations

4.1 Level of investigation

The excavation of a tunnel may cause many changes in the original soil / rock structure, such as modifying the existing stress status, to produce deformations. The reaction of soil / rock to the excavation depends on the geological and geomechanical characteristics of the soil / rock and on the excavation and support systems. A detailed knowledge of these characteristics must be obtained from geological, hydrogeological and preliminary studies (experience) in order to select the appropriate TBM type and dimensioning. This will determine the tunnel layout and help minimize the risks of tunnel instability and the modification of the surrounding environment.



The amount of detail required during the site investigation will depend on the dimension and purpose of the tunnel, on its location, on the ground conditions and existing knowledge. The greater the volume of data acquisition, the lower will be the risk of uncertainties.

The relationship between the level of investigation and the level of risks and costs is illustrated in Figure 1.1.

In general, it is unwise to go below a minimum level of investigation, to prevent the 'unforeseens' being of greater potential cost than the investigation.

Figure 1.1: Risk/data acquisition balance

(figure taken from "Guida al tunnelling", Massimiliano Bringiotti, Edizioni PEI, 1996)

4.2 Design phase

Before design can begin, it is important to collect all the available information, data and documents concerning the geology and the hydro-geological conditions of the region and the underground works already known and from similar situations.

To optimise the layout of the tunnel, the following parameters have to be taken into consideration:

- the nature of the soil / rock in the path of the tunnel (morphology, mechanical characteristics, deformability, etc)
- the position of the different layers / schists (stratagraphic characteristics)
- the direction of the main discontinuities (tectonic-structural characteristics)
- petrography
- the presence of water (hydrogeology)
- the nature of the cover and highness of the overburden
- the impact of the excavation on the environment (soil / rock stress, subsidence, hydrogeology alteration)
- buildings, traffic systems, presence of pipes and services at the surface.

Geological maps or studies are often already available. These are a useful base to define and optimise the specific investigations which will be performed to complete the necessary knowledge.

The most common investigation technologies are:

- core sampling
- test in the drilled hole, borehole measurements
- laboratory tests on samples.

The following techniques may also be appropriate:

- air and satellite photography
- geo-electric
- gravimetric
- seismic behaviour investigation
- electromagnetic radar
- geo-radar.

The geotechnical predictions should be checked for confirmation during the execution of the excavation by performing on-site tests and monitoring.

The geotechnical study, together with the geological and hydro-geological studies, should allow for:

- Interpretation of the geotechnical classification of all present materials
- determination of the conditions of stability
- dimensioning of the reinforcement and the tunnel lining properties
- identification of “critical” points of the excavation and relative precautions to be taken
- design and size of the separation plant
- selection of the driving method.

In the specific case of tunnelling in soft ground and hard rock, the following investigations should be performed:

- soil / rock identification
- determination of the initial stress conditions
- study of mechanical characteristics
- study of the hydraulic characteristics.

4.2.1 Soil / rock characterisation

Main characteristics to be identified:

Soil characterisation	*Rock characterisation*
- *soil density, wet and dry*	- *rock density*
- *water content*	- *petrography*
- *grain size distribution*	- *abrasiveness, content of quartz*
- *pore volume*	- *mineralogical analysis – where relevant*
- *abrasiveness (grain shape and hardness)*	- *elastic modulus and Poisson ratio*
- *Atterberg limits (when clay is present)*	- *cohesion*
- *mineralogical analysis – where relevant*	- *permeability*
- *elastic modulus and Poisson ratio*	- *angle of friction*
- *cohesion*	- *Unconfined compressive strength*
- *permeability*	- *Tensile splitting strength*
- *angle of friction*	- *triaxial strength*
- *undrained shear strength*	- *swelling capacity*
	- *schists / bedding*
	- *fissuring*
	- *Stability*
	- *RQD-value*

Other soil / rock characteristics may also need to be addressed such as the presence of gas, radioactivitiy or asbestos.

4.2.2 Initial Stress Conditions

The presence of deformation phenomena during the excavation will depend on the initial stress condition. To determine this characteristic is very important to know the ground history, its evolution and fracturing.

4.2.3 Mechanical Characteristics

The tunnel stability and the load on the tunnel lining will depend amongst other factors on the shear parameters and the deformation characteristics. The shear parameters (drained and undrained parameters in soft ground, the internal friction, cohesion) can be measured with laboratory and in-situ tests.

The deformation characteristic depends on the Elastic Modulus, the Deformation Modulus and the Poisson coefficient. These parameters can be determined by empirical methods. To predict the long term deformations, it would be essential to take into consideration the presence of either swelling ground or of compressible ground.

4.2.4 Hydraulic Characteristics

The presence of water not only influences the excavation works (waterproofing systems, drainage system, etc.) but may also influence the tunnel stability and the long and short terms deformation. Therefore it is important to perform a detailed hydrogeological study and thus to know the ground permeability, expected water pressure, direction of the current, seasonal and tidal variations, development of groundwater reservoirs, ph-value, etc. To determine the ground permeability, laboratory tests on samples are not sufficient and field tests are necessary.

4.3 Geological Report

The geological report should give "predictions" of the characteristics listed in the above paragraph for all the single layers which will be directly or indirectly involved during the excavation.

Other information on the material, to be excavated, which should be included in the report are:

- mechanical resistance (measured by normal laboratory tests of compressive strength and direct or indirect tensile strength, or measured with specific load tests, like the "Point Load Test" or "Franklin Test)
- hardness and abrasiveness.

  and, especially for a mechanised tunnelling project:
- fracturing generally
- number and dimension of the faults
- presence of geological discontinuities
- homogeneity/heterogeneity of the soil along the sections
- cohesiveness (stickiness) of any clays present
- permeability
- potential change of the soft ground properties with compressed air.

5. Declaration of conformity

5.1 General

This applies to product supplied in accordance with this specification.

5.2 Initial Type Testing

Testing shall be carried out by the manufacturer to prove the conformity of each product, covered by this specification, to the appropriate requirements.

5.3 Declaration of Conformity by the Manufacturer

A declaration of conformity with this specification shall be made available by the manufacturer for each product or system which satisfies the appropriate requirements in this specification.

A new declaration of conformity shall be provided following any change in formulation or in constituent materials which results in a change of the characteristics of the product.

6. Quality

The manufacturer shall operate a quality system in accordance with the principles of EN ISO 9000 at each facility where products covered by this specification are produced.

Compliance with this requirement shall be verified by an approved certification body which shall issue a certificate to each production facility where procedures have been verified.

After initial certification, an audit of each production facility shall be carried out by the approved certification body.

7. Marking & Labelling

The following items shall be indicated on the product packaging or delivery ticket:

a) Product name and grade

b) Name and address of manufacturer

c) Quantity (mass or volume)

d) Batch reference or production reference

e) Shelf life and production date, or use by date

f) Specification reference

g) Health & safety information to comply with statutory regulation.

In addition the following information shall be made available before use:

h) Product technical data sheet, with instructions for storage and use

j) Material safety data sheet.

Note: the technical data and safety information should be in the language at the place of use.

8. Environment - Health and Safety

8.1 General

The tunnelling operation and the methods of application of all associated products must meet all European and/or national regulations with regard to health, safety and environment. A general environmental risk assessment for all products used should exist in order to be able to assess the environmental risk of products used.

Generally the risk assessment study should cover effect on air, surface and groundwater, the treatment of tunnel water, handling and disposal of products and excavated material. It should also include health and safety regulations.

8.2 Health and Safety

8.2.1 Product Health & Safety information

All relevant product data (e.g. from Material Safety Data Sheets or from the literature) will be considered for the evaluation of the suitability of a particular product intended to be used at site. These should include acute toxicity data, biodegradability, bio-accumulation potential.

8.2.2 Dust

The quality of the air in the working area should not endanger the safety or the health of the workers.

8.2.3 Naturally occurring health parameters

Measures must be taken to protect workers from the effects of naturally occurring health hazards including the presence of gas, radioactivity or asbestos in accordance with national regulations in the place of work.

8.3 Environmental Risk Assessment

An appropriate Environmental Risk Assessment should be done, either based on data available from literature and previous similar studies, or in the case of lack of such information, through new testing. The study should always be carried out by a professional, certified, neutral and independent institute.

The following should be evaluated in the environmental risk assessment:

8.3.1 Groundwater and surface water

For the risk assessment on groundwater, the hydro-geological environment, e.g. proximity of wells, ground water table, water sources, dilution and water flow rates must be taken into account.

8.3.2 Recycling

All excavated materials should be recycled were possible. In the case of hard rock excavation, a part of the excavated rock may be recycled as aggregates for concrete. If chemicals have been added during excavation, for example for dust suppression or for abrasive wear reduction, comparative testing should be carried out to prove the suitability for recycling.

8.3.3 Muck disposal

The excavated material should be evaluated with regard to handling, storage, recycling and landfill.

Part 2: Soft Ground

9. Introduction to the Soft Ground TBM Operation

There is an increasing world-wide demand for conditioning of soil especially in connection with the use of both Slurry Shield Machines and Earth Pressure Balance Machines (EPBM).

Tunnel building for infrastructure projects (subways, sewers, water supply, etc) often takes place in soft ground under urban areas. The risk of settlement and consequent damage to structures above is high, and almost unlimited claims could arise. As a result of improvements to both the slurry shield machines and the earth pressure balance machines (EPBM), such risks have been reduced.

However, even the most advanced tunnel boring machine will face problems in mixed and changing ground conditions which it cannot excavate in a safe, efficient and economic way. Instead of costly changes and adaptation of the machine, even if possible, it is usually simpler to treat the ground in order to provide properties which the machine can handle.

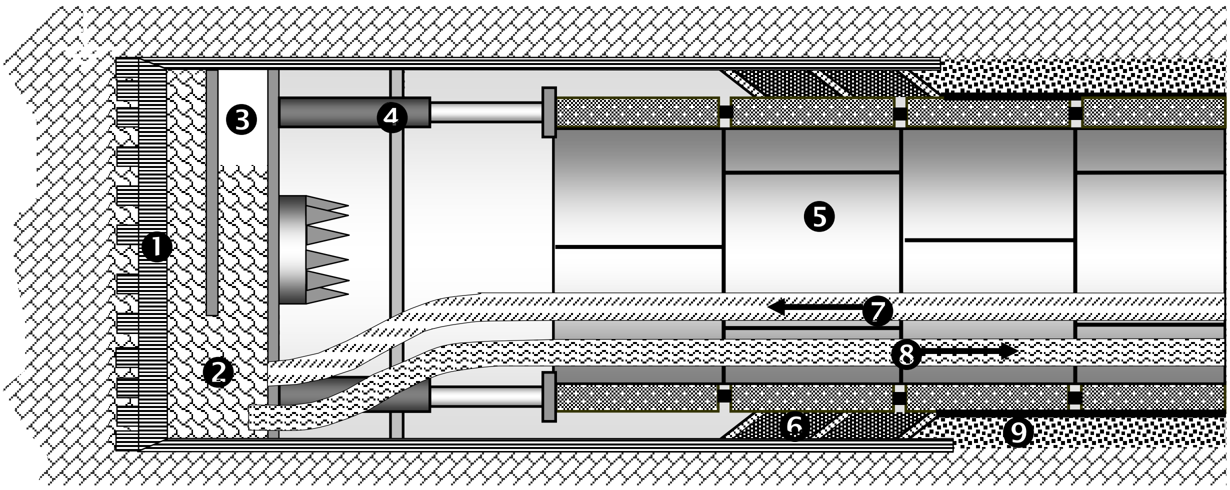
With the Slurry Shield Machine process this can be achieved by pumping water and/or bentonite slurry into the tunnel front and excavation chamber. The bentonite slurry helps to maintain an even over-pressure in front of the TBM cutter head and also acts as an aid to soil transportation by pumping.

With the EPBM technique, soil conditioning products are generally injected ahead of the cutter head and often into the working chamber and screw conveyor. By correctly choosing these products and their composition to match the requirements of the encountered soil and ground water conditions, they can:

- reduce stickiness of plastic clays (that can lead to blockage of muck conveying stystem) by TBM both with or without a shield
- lower the angle of internal friction and abrasiveness of the soil slurry (in order to reduce power for soil extraction and conveyance and also the wear costs)
- create plastic deformation behaviour (providing an even and controlled supporting pressure increases the stability of the face and reduces segregation and the consequently risk of settlement)
- adjust the soil consistency to enable tunnelling by EPBM
- reduce the soil permeability to minimise water ingress.

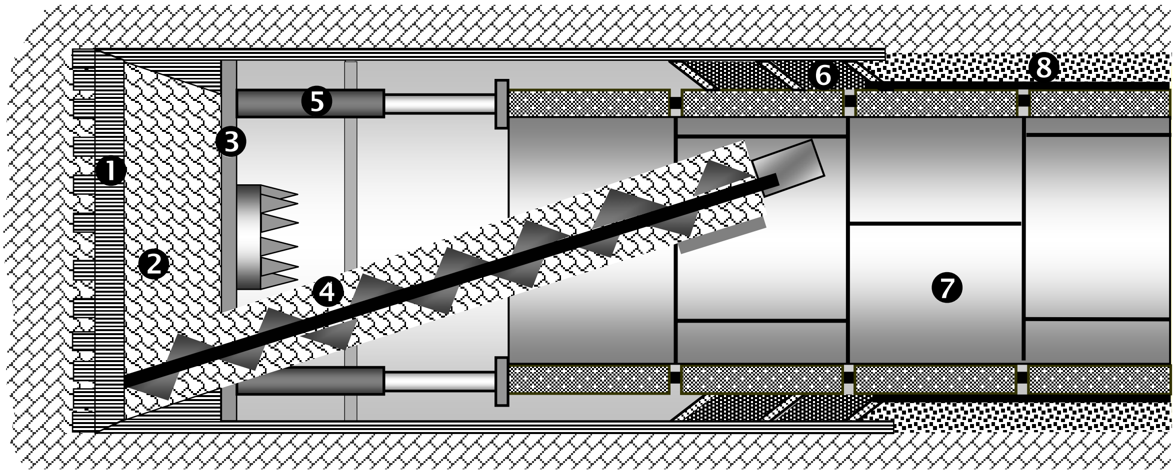
The EPBM - in comparison with the Slurry Shield Machines, makes the on-site muck handling easier and eliminates the need for a sophisticated separation plant.

The two types of TBM are shown schematically in Figure 9.1 and 9.2.



❶ Cutterhead ❷ Bentonite Slurry / Soil ❸ Air Bubble
❹ Thrust arms ❺ Segments ❻ Tail sealant
❼ Bentonite Slurry Feed ❽ Bentonite Slurry/ Soil Return ❾ Annulus Grout

Figure 9.1: Schematic Representation of Slurry Shield Machine



❶ Cutterhead
❷ Working Chamber
❸ Pressure Wall
❹ Screw conveyor
❺ Thrust Arm
❻Tail sealant
❼ Segments
❽ Annulus Grout

Figure 9.2: Schematic Representation of Earth Pressure Balanced Machine (EPBM)

10. Slurry Shield Machine

10.1 General

The slurry shield method is applicable to a wide variety of grounds, from clay to sand and gravel, with hydraulic conductivity (K) between 10^{-8} m/s and 10^{-2} m/s under varying charges of water. However, for ground with high silt or clay content, problem may result in the separation plant.

Slurry: The slurry (sometimes known as mud) helps remove the cuttings, maintaining the front face and preventing settlement, it also cools and lubricates the tools. It comprises a suspension of bentonite in water with appropriate additives. The slurry is prepared at the surface in tanks and is circulated in the slurry feeding pipe (suction line) to the front face in order to help remove the cuttings from the bore. It is then circulated out in the slurry discharge pipe.

The slurry can then be prepared for re-use. The cuttings are removed from the slurry mechanically (by shale shakers, hydrocyclones, centrifuges, etc). The slurry may require treatment to restore its essential physical properties before it is re-circulated to the feeding line.

Restoring the slurry may require dilution, addition of fresh bentonite or additives such as polymers, dispersants or pH stabilisers. This is done after checking key slurry characteristics such as density, pH, water loss, yield value (most important), plastic viscosity or solids content.

The Mud Cake is a fine membrane between the soil and the slurry which is formed at the face as water is expelled from the slurry under the applied pressure. Its role is to ensure the stability of the face, and for this it must have low permeability in order to maintain the pressure. Generally, as more water is expelled from the slurry the cake will become thicker and more impermeable. This is why the water loss must be controlled and restored where necessary by addition of fresh slurry or additives.

The effectiveness of the Mud Cake is directly linked to the properties of the slurry and to the porosity of the soil. Its primary purpose is to stabilise the particles within the soil even when it has a very low cohesion.

The quality of the slurry may be affected by contamination from the ground, either chemical or by solids. Chemical contamination can result from some materials in the ground, such as soluble sulphates or calcium salts. This may 'flocculate' the slurry so that it loses its essential characteristics by increased viscosity or water loss, etc.

The Slurry is the vital link between the Slurry Shield and the ground, and the success of the excavation will depend on its performance.

10.2 Products

10.2.1 Bentonite

Bentonite is a processed form of a particular naturally-occurring clay mineral. The basic clay mineral is montmorillonite and it may be associated with minor amounts of other minerals such as quartz, mica, feldspar, calcite, etc. The bentonite occurs naturally either in sodium or calcium form, the sodium grade having a much higher swelling capacity when dispersed in water. Calcium Bentonite can be chemically treated to obtain an activated sodium grade.

Bentonite should comply with the requirements of EN ISO 13 500.

10.2.2 Slurry additives

There are several types of polymer additives that can be used to improve the rheological properties of bentonite slurries. The use and choice of polymer additives is determined by the ground conditions. Polymers types include: Bio-polymers, CMC, PAC and Polyacrylamide. The following ground conditions can be treated with the use of polymer additives:

- Soil with high salt content. The use of polymers, particularly CMC, can make bentonite slurries less sensitive to salt contamination
- Soil with heavy clay: The use of polymers will reduce the clay dispersion, as a result, the slurry will maintain its functionality longer
- Generally, polymer additives can be used to increase the slurry yield stress and viscosity.

10.3 Performance Requirements

When excavating with a Slurry Shield Machine, the Slurry must be designed in respect of concentration, viscosity, filtration, etc, to suit the type of geology and the type of equipment used.

The primary function of the slurry is to stabilise the face. It is also required to suspend and transport the cuttings, to lubricate and cool the cutting head, and to reduce abrasive wear of the cutting tools.

The technical requirements of the slurry shall be specified by the contractor and will depend on the machine being used and the geological conditions. The programme should also detail the additional chemical dosing and mechanical treatments (screening, hydrocycloning) for re-cycling the slurry followed by the procedures for discharging waste slurry according to local regulations.

Controlling the site manufacture, maintenance and treatment of the slurry to meet the required performance requires an experienced specialist slurry engineer. The site laboratory will run tests, at regular specified intervals, to ensure the designated properties are in line with the slurry specification. If necessary, the slurry will be treated, circulating via a by-pass until the parameters are fully restored in the holding tank as well as in the circulating line.

10.4 Test Methods

The slurry test programme will generally include requirements for the following key parameters:

Characteristic	*units*	*Test method*	*Type of test*
Density - ρ	*kg/m^3*	*cylinder + scales*	*laboratory / site*
Solids content	*%*	*oven drying*	*laboratory*
PH	*-*	*test paper or meter*	*site*
Marsh fluidity - t_M	*s*	*EN ISO 13500*	*site*
Plastic Viscosity - η	*Pa.s*	*EN ISO 13500*	*laboratory – rarely measured*
Yield value - τ	*Pa*	*EN ISO 13500*	*site*
Filtrate water	*m^3*	*EN ISO 13500*	*laboratory / site*

Tests for these characteristics are described in EN ISO 13500, which is a standard written primarily for drilling fluid materials used in the petroleum and natural gas industries. However the relevant tests are identical. The standard also specifies the properties of raw materials other than Bentonite which may be used in the formulation of the slurry.

10.5 Mixing Equipment

The preparation of bentonite-based slurries on the job-site requires the correct mixing equipment to guarantee an optimum yield of the product.

Bentonite, a naturally occurring mineral that does not readily disperse in water, particularly in cold water. Homogenization of a bentonite slurry becomes more efficient when the clay particles are fully hydrated and the conglomerates become broken down. The process of dispersing bentonite in water aims to obtain the most complete mechanical disintegration of the particle conglomerates in order to accelerate the hydration by increasing the surface area of the particles. However, being a processed clay, the presence of mineral and/or organic compounds potentially added during the production may also influence the ability of the bentonite to be dispersed into the water.

It is important to use the appropriate mixing equipment which will allow a quick and complete hydration of the bentonite. On a tunnelling job-site as for all other applications using bentonite based fluids, it is better not to use the fresh bentonite slurry immediately but to store it in an adapted storage tank where hydration can continue.

Preparation of the slurry will be achieved using a mixing tank equipped with a powerful centrifugal mixer pump to circulate the fresh bentonite slurry for several minutes before transferring it to the main storage tank. If the mixing is efficient, the full properties of the bentonite suspension would be substantially achieved within a few hours. However, the viscosity of the prepared slurry should be monitored to ensure full hydration is reached.

To maintain the slurry properties it may become necessary to add further additives to the bentonite slurry. In such a case, the contractor should anticipate this possibility by asking the manufacturer of the slurry treatment plant to include dispensing devices that will facilitate the introduction of these chemicals.

11. Earth Pressure Balanced Machine (EPBM)

11.1 General

A modern EPBM drive combines a knowledge of three main subjects:

- Soil mechanics (pressure support and soil characteristics)
- TBM technology (cutterhead design, installed force, ...)
- Soil conditioning additives.

Only a good comprehension and interaction between these aspects will result in a successful TBM drive and commercial success.

The control of face support is a major issue in EPBM tunnelling. Continuous support of the tunnelling face must be provided by the excavated soil itself, which should completely fill the working chamber. The required support pressure at the tunnelling face will be achieved through:

- Thrusting the shield forward - by means of hydraulic jacks - against the soil mass (force equilibrium)
- Regulation of the screw conveyor-rotation (volume equilibrium).

The support pressure has to balance the earth pressure and the water pressure. Depending on soil characteristics and the cover to diameter ratio (t/D) different types of earth pressures are to be determined.

11.2 Area of application for EPBM excavation

Figure 11.1 indicates typical particle size distributions for the use of EPBM, It can be used as a guide in order to give an idea of the soil conditioning needs in different ground types.

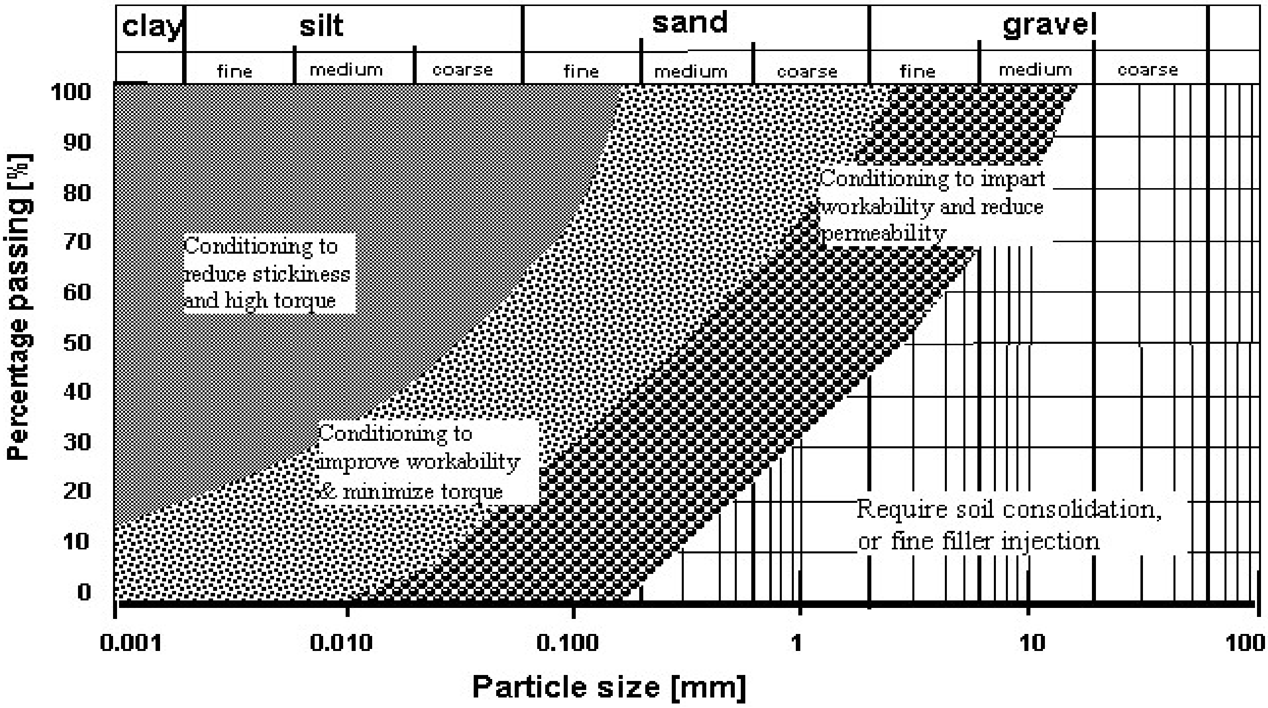


Figure 11.1: Soil conditioning needs of EPBM in different ground types (Boundaries are only indicative)

11.3 Products used for soil conditioning in EPBM Tunnelling

EPBM tunnelling generally requires the use of additives which make it possible to cut, support and transport the soil with economical boring parameters. Soil conditioning can be achieved by addition of foam and/or additives. The selection of the foam type and the additive depends mainly on the soil type in situ but also on the characteristics of the TBM.

Types of additives include special anti-clogging agents to avoid clogging problems, anti abrasion additives for the cutterhead and its tools as well as for the extraction screw.

Bentonite and/or fine particles can be added to soils with lack of fines and this can also provide support for polymer and foam additives. Other additives are used to avoid segregation and reduce the permeability of the soil.

11.4 Product Performance Requirements

The following product types are intended to achieve one or more effects:

- foam:

  maintenance of pressure, fluidising effect for the soil, creation of an homogeneous soil paste, permeability reduction, lowering of torque, reduction of soil stickiness, reduction of abrasion

- anti-clogging agents:

  mainly used for heavy clay soil

- other additives:

  structuring effect on non-cohesive soils, stabilising of foam or soil, water retention, viscosity effects

- anti-abrasion agents:

  to add to very abrasive soils or rock formation, to reduce wear of the cutting head and its tools, extraction screw.

These product should be environmentally acceptable and safe to handle with normal site precautions.

11.5 Foam

11.5.1 Soil conditioning: choice of foam types

The Foam type chosen should match the properties of the soil to be excavated - see figure 11.2.

Foam type A: high dispersing capacity (breaking clay bonds) and / or good coating capacity (reduce swelling effects)

Foam type B: general purpose, with medium stability

Foam type C: high stability and anti segregation properties to develop and maintain a cohesive soil as impermeable as possible.

	Foam types				*Polymer additives*
Soil	*A*	*B*	*C*	*FIR*	
Clay				*30-80*	*Anti clogging polymer*
Sandy lay – silt				*40-60*	*Anti clogging polymer*
Sand – layey silt				*20-40*	*Polymer for consistency control*
Sand				*30-40*	*Polymer for cohesiveness and consistency control*
Clayey ravels				*25-50*	*Polymer for cohesiveness and consistency control*
Sandy ravels				*30-60*	*Polymer for cohesiveness and consistency control*

Figure 11.2: Product types for EPBM relative to different soils (FIR values are indicative only)

11.5.2 Guidelines on use of Foams:

- **Foaming solution**

  The concentration of foaming solution CF is typically in the range 0,5 - 5,0%, but should follow the manufacturer's recommendations. This concentration strongly depends on the amount of water which is injected or which is already present in the soil and also affects the activity and stability of the used tunnel foam.

  C_F - concentration of surfactant agent in water (→ foaming solution)

  $C_F = 100 \times m_{Surfactant} / m_{Foam\ Solution}$

  $m_{Surfactant}$ mass of Surfactant in Foaming Solution

  $m_{Foam\ Solution}$ mass of Foaming Solution

- **Foam Expansion Ratio FER**

  The FER should be at 5 – 30. The higher the FER, the drier a generated tunnel foam will be. The wetter a soil, the drier a tunnel foam should be and vice versa.

  FER - Foam Expansion Ratio

  $FER = V_{foam} / V_{Foam\ solution}$

  V_{foam} Volume of foam at working pressure

  $V_{Foam\ solution}$ Volume of foaming solution

- **Foam Injection Ratio FIR**

  The FIR can be at 10 – 80%, in most cases around 30 – 60%. To determine the best FIR value, laboratory tests have to be carried out. The water content of the soil or the amount of injected water plays an important role.

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

  V_{Foam} Volume of Foam at working pressure

  V_{Soil} Volume of in situ soil to be excavated

11.5.3 Test Methods for the Foam

This section describes some parameters as starting points for understanding basic properties of the foam to be used. At this stage the tests should be considered as comparative and not absolute, as the tests will only provide an initial indication of the effectiveness of the foaming agent or foaming agent/polymer combination. Only tests with the actual soil and under equivalent TBM conditions can prove the true efficacy of such products. The correlation on foam volume and pressure can be demonstrated. The compression and expansion of foam under pressurised conditions is a reversible process. This also applies to foam / soil mixtures. The tests given in Annex A set out to determine some of the properties of a foam under controlled conditions, albeit at atmospheric pressure.

The standard sand used in the test could conceivably then be replaced by soil from the project and the tests repeated where appropriate to give a better degree of correlation. Other standard sands could be used provided comparative testing is first carried out.

Key Parameters are:

- Foam density

  from this the FER can be calculated;

- Foam Stability (Half -life) (Annex A.1)

  determination of the half life of the pure foam under atmospheric pressure;

- Stability (Half-life) of a foam when mixed with a standard sand (Annex A.2)

  or soil from the project;

- Plasticising effect of the foam (Annex A.3)

  assessed by the mortar flow table.

Experience of operating these tests is limited at present, but it is hoped that subsequent experience gained with these tests will enable indicative limits to be recommended for manufacturers to adopt. For the present, the procedures will enable comparative tests to be carried out for different foams.

11.6 Anti clogging additives

In highly cohesive ground with high clay content, the anti clogging additives can be used to prevent the clay from clogging of the cutter head, to reduce drive torque, and to make it possible to fill the working chamber.

11.7 Polymer Additives

In some cases polymers can be added to improve foam stability or adjust the consistency of the soil passing through the working chamber and screw conveyor. A typical example might be in wet, sandy soils with little cohesion. See figure 11.2.

12. Tail Shield Sealant

12.1 General

The sealant compound shall be designed to seal the tail end of the TBM against ground water (fresh or marine), grout and bentonite slurry (if used). It shall have:

- Good resistance against water and grout pressure
- Good anti washout properties
- Good wear protection for the brushes
- Good pumping properties over a wide range of temperatures
- Good adhesion to concrete and metal
- Good stability (no fluid separation) in storage and under pressure
- No harmful effect to the sealing gaskets.

12.2 Performance Characteristics

Characteristic	*Class A*	*Class B*	*Class C*
Water Resistance to 8 bar for 5 minutes *(test method – Annex B)*	*Pass 1.0 mm mesh in > 5 minutes*	*Pass 0.5 mm mesh in > 5 minutes*	*Pass 0.5 mm mesh in < 5 minutes*

Figure 12.1: Tail Shield Sealant Performance characteristics

Other characteristics such as density, colour, odour, consistency, flash point should be as described by the product manufacturer and should conform to their stated limits.

13. Annulus Grouts and Mortars

13.1 General

This chapter deals with annulus grouts for Shielded Tunnel Boring Machines, where lining segments are erected inside the shield. In a hard rock TBM it is usual only for an invert segment to be present. However, this chapter is deemed to be appropriate also for filling the void beneath the segment in this case.

During the construction of a tunnel with a shielded TBM a void is created behind the segments which needs to be filled with a pressurised grout or other similar material. Failure to do this results in ground subsidence, asymmetrical loads on the concrete segments and possible damage or leakage through the tunnel gaskets.

This chapter is designed around performance requirements rather than prescriptive requirements. This allows more imaginative use of materials and allows for the most effective solution for a particular application.

13.2 Requirements

13.2.1 Structural Requirements

Grout is the important link between the surroundings (soil or rock) and the structure (precast segments). The reasons for using a grout can be summarised as follows :

- To prevent flotation and heave
- To prevent surface subsidence
- To prevent misalignment of the segment rings
- To bond the soil and segments into a single component.

The grout may be pumped into position either through the tailshield or through holes in the segments and needs to provide early support in the build area.

13.2.2 Logistical requirements

There are also logistical requirements to be fulfilled due to mixing , transporting and placing of the grout. These will depend on the nature of the project and will vary accordingly.

However, the grout:

- Should be pumpable from the mixer or agitator to the point of placing without segregation or bleeding, irrespective of the distance or time involved
- May need to remain workable for an unspecified period (up to 24 or 48 hours) for long or difficult delivery schedules
- May need to stiffen or set quickly to provide rapid support to (invert) segments, or to achieve an early strength to reduce subsidence or prevent water washout.

13.3 Constituent Materials

13.3.1 Cement

The cement shall conform to EN 197-1.

13.3.2 Fine Aggregates

Aggregates where used should preferably conform to local or EN 12620 standard requirements and should be clean and free from impurities that would have a deleterious effect on the grout.

13.3.3 Water

Water shall be of potable quality or shall comply with the requirements of EN1008 or be from a supply which has been shown by tests to be of suitable quality .

13.3.4 Admixtures

Admixtures should conform to EN934 Parts 2 or 5, where relevant. However, non-standard admixtures may be used after tests to confirm their suitability.

The use of admixtures falls into various categories :

- Plasticizers and Superplasticizers with or without the inclusion of accelerating or retarding properties
- Retarders and Accelerators without any plasticizing property
- Air entraining admixtures
- Foaming admixtures
- Hydration Control Stabilisers
- Consistency Control Stabilisers and systems
- Other admixtures not falling into any category such as Bentonite, Thickeners, Stabilisers or non-shrink agents.

13.3.5 Additions

Additions can be described as being either hydraulic (pozzolanic) or non-hydraulic. Examples are ;

Hydraulic/pozzolanic (Type II)

- Fly Ash
- Silica Fume
- Blast Furnace Slag
- Nanometric silica

Non-hydraulic (Type I)

- Limestone powder
- Finely divided quartz flour
- Bentonite

13.4 Annulus Grouting Method

Grouting can be carried out :

- Through channels in the tail shield in which case a method for rapid cleaning of the grout channel is required in the event of a stoppage or blockage;
- through holes in the segment.

In either method the grouting may involve one or more admixtures to provide better control over the properties of the grout.

Also, to avoid ground settlement:

- Grouting of the cavity should be carried out in a continuous operation through the tailshield, or as soon as possible when injected through the segments.
- Should subsequent testing reveal that the initial grouting did not completely fill the void then a second grouting stage will be carried out to complete the works.

13.5 Types of grout

Types of grout can be sub-divided into three categories:

- Active

  In the Active system full hydration of the binder component occurs such as with grouts containing higher percentages of Portland cement e.g. >300 kg/m3.

- Semi-inert

  In the Semi-Inert system the grout is mainly composed of the same elements as found in the Inert type with the addition of a small percentage of a material that will cause a degree of hydration to occur; e.g. <100 kg/m3 Portland cement. But essentially the grout may take a considerable period of time to harden although stiffening will occur more quickly.

- Inert

  In the Inert system the system contains no Portland cement , mainly hydraulic lime.

The selection of the type of grout will depend on the particular tunnel requirements, such as the risk of settlement the need for waterproofing and the soil conditions.

A second sub-division can be described as:

- Single component
- Two or more components.

Additions such as Bentonite , Fly Ash ,Slag and/or Silica Fume may be used to improve aspects of the grout properties such as bleeding or pumpability.

The smallest hose or line through which the grout will pass will need to have a diameter at least 3 times greater than the maximum particle size of the aggregate use in the grout.

Admixtures and additions as mentioned above may be allowed by the Engineer , but products and materials containing calcium chloride are not permitted.

In all cases, the proportions of the various constituents will vary to suit the site conditions and overall requirements of the works with the objective of providing a suitable mix. Trials will be required to ensure the mix design meets the pumping and performance requirements.

13.6 Characteristics

The general characteristics of the grout and the working procedure shall satisfy the following requirements;

- In the short term the grouting procedure shall prevent settlement prejudicial to the safety of the environment
- In the long term the grout shall be a factor for water-tightness and durability of the tunnel.

The grout shall have the following characteristics:

- have a minimum water content sufficient to allow pumping but resist segregation;
- be of a suitable consistency and workability to fill the void created during shield advancing;
- have limited shrinkage during and after hardening;
- set or stiffen quickly, where required to avoid settlement;
- resist segregation and bleeding in order not to block lines, pumps and tailseals (less than 1%);
- resist wash-out from water entering the void from the surrounding soil;
- provide a long term homogenous, stable and low permeability ring around the tunnel lining.

Accordingly the following aspects should be taken into consideration:

- the grout composition and type of admixtures and additives
- the setting and rheological characteristics of the grout
- the working conditions, shrinkage characteristics and injection pressures taking into account the results from site investigations and the location of the water table
- the long term durability and strength requirements of the grout
- quality control procedures and testing (both in the laboratory and in the field): in particular the volume injected for each ring compared to the theoretical volume. If the amounts injected are shown to be insufficient or the grouting imperfect ,secondary grouting as a complementary treatment shall be performed as soon as possible.

13.7 Performance Requirements

All grouts shall have the following essential requirements:

13.7.1 Single component grouts

Characteristic	*Test method*	*Requirement*
Bleeding	*EN 480-4:1997*	*Less than 1% up to the initial set or initial stiffening time in the case of Active and semi-active grouts or 72 hours in the case of an Inert grout.*
Setting time for Active grouts *Method will depend on maximum aggregate size:* *0 –2 mm:* *>2mm:*	*Vicat test to EN 413:1995* *Penetration test similar to setting time method of EN 413:1995* *Temperature to be ±1°C of the temperature used in the proving trials*	*Initial setting time within +3 h and –15 min of the stated setting time.* *Final setting time not later than* *4 h after initial setting time.*
Stiffening Time for Semi-Inert grouts	*as above*	*Initial setting time within +4 h and – 1 h of the stated setting time.* *Final setting time not later than 12h after initial setting time.*
WORKABILITY		
Slump test	*EN 413-2:1995*	*± 25mm of stated Slump value*
Spread Table	*ASTM C230*	*± 10% of stated Spread*

Figure 13.1: Plastic Consistency for single component grouts

13.7.2 Two component grouts

These can be loosely described as Component A, a stabilised main component, and Component B, which can described as the activating component of the system.

Two component grouts fall into two categories:

- Mortar consistency Component A with a liquid Component B

  Component A should have the plastic consistency properties described in figure 2.6 with the exception of setting time requirements.

  The Component B properties should be as described by the manufacturer or supplier of the product.

  The combination of the two components should meet the requirements as specified by the Contractor or by the project specification.

- Liquid consistency Component A with a liquid Component B

  Component A and Component B are generally high fluidity products. In this case Component A should still match the requirements in figure 2.6 with the exception of the Setting time and workability clauses.

  The workability of the Component A should be measured by a Marsh Cone and should give a flow time within 15 seconds of that recommended by the supplier of the admixtures.

  The quality of the Component B should be determined by regular tests or by a Quality Assurance certificate provided by the manufacturer.

The combination of the Component A and B should be carried out by pouring the recommended proportions of each into a grout-tight container with minimal stirring. The setting time should be determined by Vicat Needle when the penetration of the needle leaves an indentation of less than one millimetre from the surface. This time is generally short e.g. less than 20 seconds. The result should coincide with the needs of the project and/or the specification.

13.7.3 Hardened Properties

The hardened properties of a grout for annulus grouting are generally minimal but where they are specified the clause below should be followed.

Characteristic	*Test method*	*Requirement*
Compressive Strength	*BS EN413*	*As determined by the Engineer to meet loads and pressure requirements from the surrounding environment and support for the segment rings.* *Sampling rate to be decided based on advance rate and tunnel size.* *Tests to be carried out on 3 specimens per age of test from the same batch.* *The minimum strength value should not be less than the minimum requirements.* *Non-compliance action to be decided by the Engineer.*

Figure 13.2: Hardened Properties of grouts

13.8 Specification for Grouting Equipment

13.8.1 Introduction

The equipment used to mix and place the grout is as important as the quality of the grout materials. The mixing equipment directly influences the properties and quality of the grout.

The pumping equipment used for the trials and for the grouting must be suited to the nature of the work and fully able to meet the requirements of the project. A number of different types and manufacturers of pumps exist and there is not necessarily one more suitable than the others. Some of the more common are various piston and worm/stator (mono) pumps as well as peristaltic types.

The type, size and the numbers of each type of equipment will vary from project to project and will depend on the dimensions of the work, the pumping distances and special needs of the works. It is therefore impossible to set definitive specification requirements to meet all applications. The specification set out is, therefore, of a general nature.

However as a general rule, the capacity of the mixing plant and storage tanks should be sufficient to grout at least a complete ring without stopping.

Wherever possible the mixing and pumping equipment should correspond in capacity to the TBM advance rate and segment erection rate. The pressure to which the grout is pumped and the pressure developed behind the segment should be controllable and an automatic pressure cut-off installed to limit surge pressures. In addition measures should be taken to control the volumes of grout injected.

13.8.2 Mixing Equipment

The mixing equipment shall be of such capacity to mix sufficient grout for each ring. The mixing time shall be as short as possible consistent with complete mixing of the ingredients.

Mixing shall be carried out in a forced action mixer. Agitator trucks, “trixers” or other forms of agitators shall not be allowed for mixing purposes. Depending on the type of grout to be mixed a low shear or a high shear mixer may be used.

Minimum mixing times shall be determined by full-scale trials on the mixing plant to be used and the proposed materials for the grout.

The arrangement of mixer paddles shall be such that no “dead zones” exist in the mixer.

- Reference shall always be made to the manufacturer’s instructions for use and recommendations for maintenance.
- Weigh hoppers and scales shall be calibrated as part of a pre-determined Quality Assurance scheme: detailed records of calibration shall be kept, also of any major errors noted. Re-calibration shall be carried out at least every month of operation or sooner if laboratory results indicate variations in grout quality.

13.9 Batching

- **Powder and Dry Ingredients**

  The powder ingredients used in the grout shall be weigh batched into the mixer or holding hopper. The accuracy of batching shall be to ± 2.0% of each material in the mix design. Volume batching of any of the ingredients shall not be allowed.

- **Water**

  Water shall be either weigh batched or may be added via a flow meter. In either case the accuracy of addition shall be ± 1.0% of the specified quantity in the mix design.

- **Admixtures**

  Liquid admixtures shall be added via an accurate dosing pump, or liquid weighing tank designed for the purpose. The accuracy of addition shall be to ±5% of the specified quantity in the mix design.

Powder admixtures shall be added via an accurate weigh hopper designed for the purpose. The accuracy of addition shall be ±5% of the specified quantity in the mix design. Each admixture shall be dispensed through its own dosing equipment. Admixtures should ideally be dosed into the water stream at mixing time. Weigh hoppers, scales and flow meters shall be calibrated as part of a Quality Assurance scheme or independent of such a scheme. However, records of calibration shall be kept. Re-calibration shall be carried out at least every month of operation or sooner if laboratory results indicate variations in grout quality.

13.10 Batching Sequence

The sequence of batching each of the materials in the mix will vary with composition and the proposed mixing equipment. Tests shall therefore be carried out with the batching and weighing equipment to determine the sequence of addition that provides the optimum mixing efficiency in the shortest time and gives a consistent quality grout. Tests on the mixed grout shall include a workability test and density test. In addition setting and strength tests shall be carried out if appropriate or specified.

13.11 Transporting the Grout

The grout may be transported in various ways. However, they shall meet the requirements of the following: Drum agitator trucks or “trixers”: no water shall remain in the truck after cleaning operations. Any openings shall be covered to prevent water or dust ingress during transportation.

13.12 Pumping equipment

The pumping equipment shall provide a constant flow of grout to the point of grouting. To prevent loss of paste from the grout the inside of the grout lines shall be pre-wetted with a 1:1 by volume cement slurry or grout or other suitable material. Water alone is not considered sufficient. This is particularly important where fine sand forms a part of the grout composition. Grouting shall not commence until the bulk of this weak mixture has been pumped through the lines and properly mixed grout is observed. Reference shall be always made to the manufacturer’s instructions for use and recommendations for maintenance.

13.13 Back-Grouting Operations

The Engineer shall approve the method and equipment proposed for filling the annular void. The proposals shall include details and location of the mixing plant and grout pumps, the mix design, methods of monitoring grouting procedures and volumes, recording and controlling the sequence and timing of grouting, the method of preventing grout leakage and details of the experience of the personnel and supervisors.

Part 3: Hard Rock

14. Introduction to the Hard Rock TBM Operation

Tunnel boring machines (TBM) have been used in hard rock for several decades and a great deal of experience has been gathered. A distinction is made between open gripper-type TBMs with conventional methods of rock support and shield machines with a tubbing-type (segmented) lining. However, the excavation process for the drilling head is identical for both processes.

A cutter head, rotating on an axis which coincides with the axis of the tunnel being excavated, is pressed against the excavation face; the cutters (normally disc cutters) penetrate into the rock, locally pulverizing it at the contact surface between the ring and the rock, creating intense tensile and shear stresses. As the resistance under each disc cutter is overcome, cracks are created which intersect and create chips. Special buckets in the cutter head allow the debris to be collected and removed to the conveyor belt.

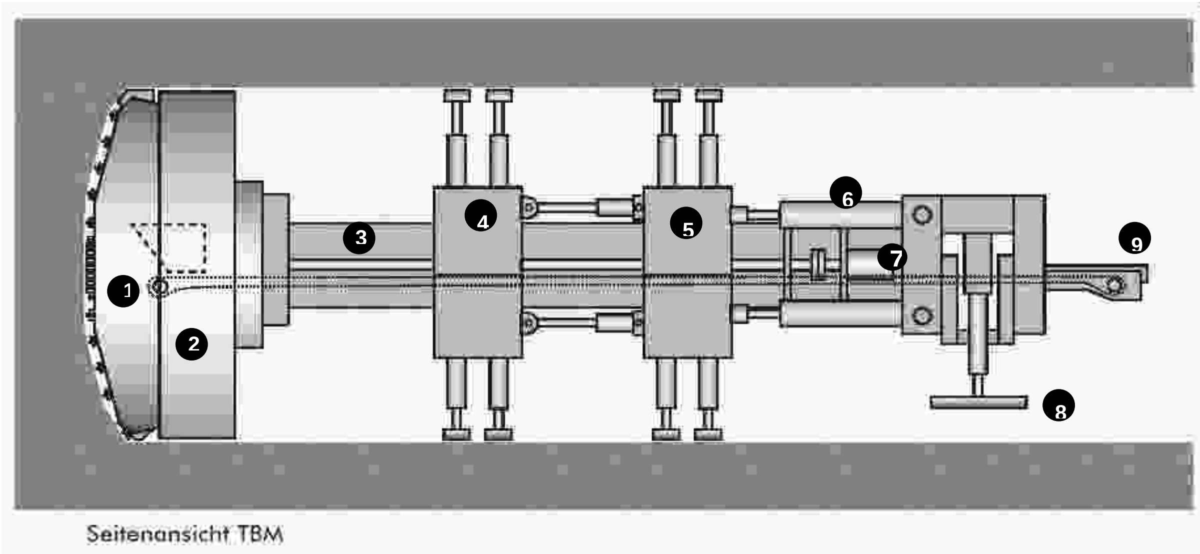
The open TBM uses its gripper system to support itself laterally on the tunnel walls, so that the driving force is brought to the drilling head. The shield TBM has presses which support themselves longitudinally on the tubbing lining, enabling the forces to be conveyed to the drilling head in the direction of driving. Hard rock is normally a problem for cutters. The cutters become damaged and/or heavily worn and the penetration rate is reduced. Frequent cutter inspections and changes reduce the utility time of the TBM. Great efforts are constantly being made to increase the quality of cutters. Much can be achieved by improving the steel quality in the rings and increasing the size of the cutters.

The heat that is generated in the cutters by working on hard rock increases cutter wear, and may lead to an increased occurrence of cutter clogging which further increases wear on the cutter heads. Wear on the cutters results in higher costs and increased TBM downtimes. To counteract this problem, chemical products have been developed to reduce, clogging, abrasion and wear on the cutter head.

An additional problem in dry hard rock is caused by the production of dust due to the fine particle size (chips) of the material excavated by the TBM.

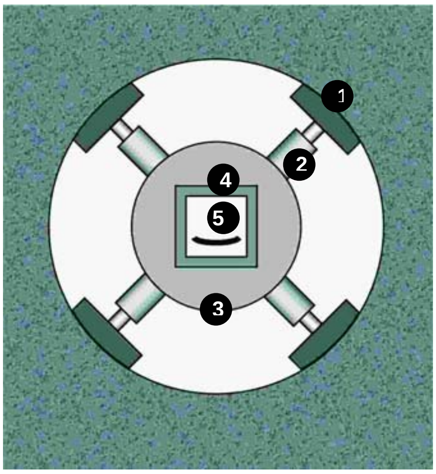
This part of the guideline only covers ways of reducing cutter wear and improving the dust control in hard rock TBM applications. Other hard rock problems are not covered by this guideline.

Schematic Representation of a Hard Rock Tunnel Boring Machine



1 Cutter Head	**4 Front Gripper System**	**7 CH-Drive Motors**
2 Cutter Head Jacket	**5 Rear Gripper System**	**8 Rear Support**
3 Inner Kelly	**6 Thrust Cylinder**	**9 Muck Conveyor**

Figure 14.1 Side View of a Hard Rock TBM.



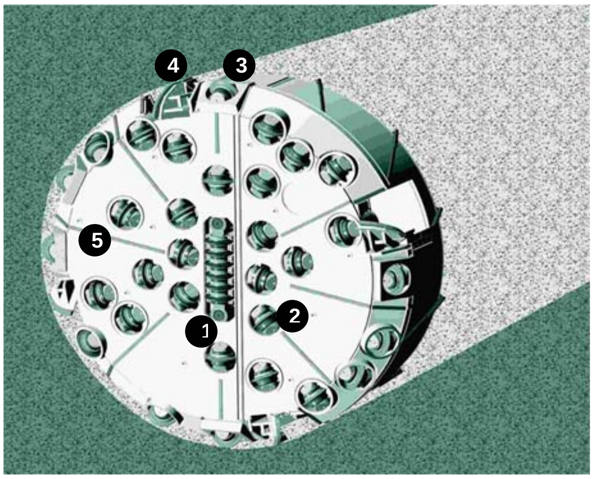


Figure 14.2: Gripper System

1 **Gripper Pad**
2 **Gripper Cylinder**
3 **Outer Kelly**
4 **Inner Kelly**
5 **Muck Conveyor**

Figure 14.3: Cutter Head front view

1 **Centre Cutter**
2 **Face Cutter**
3 **Gauge Cutter**
4 **Scraper**
5 **Wear Plates**

15. Wear

15.1 Cutter disc wear in hard rock TBM tunnelling

In hard rock TBM tunnelling, one of the most important economic factors is related to cutter wear. This is in part caused by risks involved in the interpretation accurately of site geological data, hence the difficulties in predicting accurately in advance cutter replacement frequency. High cutter wear not only leads to high cutter replacement cost, it also increases TBM downtimes and reduces TBM advance rates. Replacing cutters is a time consuming process and invariably brings the TBM to a standstill.

The main factors that affect cutter wear are:

- Cutter characteristics
- Properties of rock (strength, hardness, abrasively, quartz content)
- Effect of Water
- Temperature.

15.2 Rock abrasivity characterisation

The abrasivity of rock is affected by a number of parameters related to the rock. The main ones are described below.

15.2.1 Unconfined Compressive Strength (UCS)

UCS is the most basic strength parameter of the rock, which gives an indication of rock boreability. It is easily determined on cored rock samples, using standard test method, for example, ASTM D2938.

UCS is calculated by dividing the maximum load at failure by the test sample's cross section area:

$\sigma_c = F / A$

Where: σ_c – UCS

F – Maximum failure load

A – Cross sectional area of core sample.

15.2.2 Indirect Tensile Strength (Tensile splitting strength)

Indirect tensile strength provides a measure of the toughness of the rock as well as its strength. Standardised test methods are available, for example, ASTM D3967. It is measured by applying a load perpendicular to the axis of the core sample. It is calculated according to the following formula:

$\sigma_t = (2 * F) / (\pi * L * D)$

Where: σ_t – Indirect tensile strength

D – Diameter of core sample

F – Maximum failure load

L – Core sample length.

15.2.3 Rock Moh's hardness

Moh's hardness is a relative indicator of a mineral's resistance to scratching against other minerals. A Moh's hardness class can be assessed based on the percentage of the typical abrasive mineral content. The higher the Moh's hardness class, the more abrasive the rock is. Quartz is a mineral with one of the highest Moh's hardness class. Rock with a high quartz content normally has high abrasivity.

15.2.4 Cerchar abrasive index (CAI)

The Cerchar abrasivity index is a scratch and wear test. A series of sharpened steel pins of a known hardness alloy steel are used to scratch the surface of a freshly broken rock. A static load of 7 kg is applied. The abrasive index is determined by the resultant wear on the steel pins. By choosing the same type of steel for the test pin as the cutter, it is possible to use the CAI as an indication of cutter wear rate.

Category	*CAI*
Not very abrasive	*0.3 – 0.5*
Slightly abrasive	*0.5 – 1.0*
Medium abrasive	*1.0 – 2.0*
Very abrasive	*2.0 – 4.0*
Extremely abrasive	*4.0 – 6.0*

Figure 15.1: rock abrasivity classification using CAI index

CAI >>	*Range*	*Middle value*	*1 2 3 4 5 6*
Sandstone with clay/carbonate cementation	*0,1 – 2,6*	*0.8*	---o----------
Limestone	*0,1 – 2,4*	*1.2*	----o-----
Sandstone with SiO_2 cementation	*2,3 – 6,2*	*3.4*	-------o------------------
Basalt	*1,7 – 3,5*	*2.7*	-------o------
Andesite	*1,8 – 3,5*	*3.0*	------o----
Amphibolite	*3,0 – 4,2*	*3.7*	----o----
Schists	*2,0 – 4,5*	*3.2*	-------o-------
Gneiss	*2,5 – 6,3*	*4.4*	----------o--------------
Syenite / Diorite	*3,0 – 5,6*	*4.6*	--------o------
Granite	*3,7 – 6,2*	*4.9*	-------o----------

Figure 15.2: CAI values of some commonly encountered minerals

15.3 Disc Cutters

Despite considerable advances in cutter technology in the last decade, cutters remain one of main limiting factors in improving the performance of hard rock TBMs, due to the maximum thrust load that each cutter is able to take, and the high abrasive wear to the cutter disc in abrasive ground.

Cutter's design can vary from manufacturer to manufacturer. A typical one is shown in the diagram below:

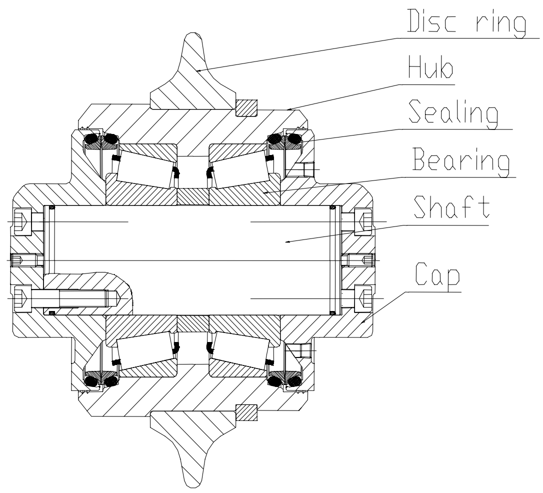


Figure 15.3: Typical disc cutter design

The basic components of a cutter are: the shaft, the bearing assembly, bearing housing, bearing sealing, the steel cutter ring or disc, the cutter ring hub.

Cutter wear normally relates to the abrasive wear on the cutter disc. First of all, cutter wear is a time dependent property: The longer the service time, the higher the wear. Cutter wear also depends on the abrasiveness of the rock.

The ratio of the cutter disc steel hardness to the rock hardness plays an important role on the rate of wear. In order to reduce wear rate, this ratio should be maximised. However, high steel hardness is achieved at the expense of another important property, toughness. Toughness of the steel is related to another type of damage to cutter discs: fracturing and chipping. Normally, hardness and toughness need to be optimised in relation to each other for the cutter discs, depending on the types of rock.

Other types of cutter damage are related to bearing or hub failure, overload, etc.

15.4 Cutter disc wear reduction

15.4.1 Cutter design & material optimisation

Cutter design optimisation involves finding the most effective design for the hub and bearing assembly, to ensure even and consistent thrust load distribution on the cutter discs, and maximum resistance against bearing seizure and other types of damage.

Cutter material optimisation is affected by the rock type and involves balancing cutter disc steel composition and heat treatment, in order to obtain the right balance of hardness and toughness, so that both abrasive wear and chipping can be minimised.

15.4.2 Water

Water is invariably used in hard rock TBM excavation to dampen and suppress dust formation. A secondary function is to cool the cutters as high temperature may lead to increased wear and damage. During the TBM advance, water is injected through numerous nozzles located across the front of the cutter head. Typically up to 1.5 lit of water per cutter/min can be used.

Small scale laboratory tests have shown, that at constant temperature, excessive water can increase abrasive wear.

15.4.3 Anti wear additives

The technology is based on special anti wear polymers that are injected to the cutterhead in the form of foam. The foam ensures the optimum distribution of the lubrication polymer across the excavation face.

In addition to reducing abrasive wear, anti wear additives can also improve cooling to the cutterhead, improve mucking, and suppress dust formation.

15.5 Application requirements

Current state of the art hard rock TBMs are equipped with a water spraying system. This normally includes 1 water supply line to the cutterhead, a splitter box and small diameter pipework (12 mm) to the different injection points on the cutterhead. Sometimes the injection points are equipped in addition with sprinklers in order to create a fine water spray.

The use of Anti-Wear Additives requires a change or update of this water spraying system:

- Installation of foam generator

  The foam generator can be manually controlled but fully automatic ones are preferable because failures can be easily detected from the TBM control room.

- Installation of rotary coupling for both water and foam injection

  The rotary coupling ensures that 1 foam gun is directly linked to only 1 or 2 injection points on the cutterhead. This enables the setting of different foam parameters to defined injection points, which is necessary to obtain increased foam quantity on the cutterhead periphery. The rotary coupling has to have as many foam lines as the foam generator, plus an additional 1 or 2 water lines. This makes it possible to inject both water & Foam on the cutterhead through different injection points.

- Installation of bigger diameter pipe works (minimum 25 mm)

  If the existing pipe work to the injection points is less than 25 mm, the foam will be unstable and decomposes back into water & air before reaching the injection points.

- Additional installation of foam injection ports and pipe works

  The water sprinklers destroy the foam. Water spraying systems need to be shut down during the operation with foam.

The dimensioning of the number of foam guns is recommended as follows:

- TBM diameter <3m: 1 gun
- TBM diameter >3m and <5m: 1 - 2 guns
- TBM diameter >5m and <7m: 2 - 3 guns
- TBM diameter >7m and <9m: 3 - 4 guns
- TBM diameter >9m: 4 – 5 guns

16. Dust control

The chapter concentrates on the dust formed by the excavation process and not from other processes during the tunnelling operations such as rock support.

16.1 Dust formation

In hard rock TBM tunnelling, the cutters located on the cutterhead rotate continuously under a strong thrust force on the rock face causing the rock to crack and form chips, allowing excavation to take place. As cutters impact on the rock, and during its continuous rotation on the rock face, rock dust is formed, which rapidly becomes air-born due to high air turbulence. The air born dust soon find its way through any openings, forming dust clouds in the TBM working area just behind the TBM cutterhead.

Rock chips are normally transported by conveyor belt to the surface. Transfer points are also locations where rock dust can become air-born and create high dust concentration.

High concentration of fine dust in the TBM working area and in the area behind it can be a cause of eye and respiratory irritation to the TBM operators. In the case of silica dust, it may also cause silicosis. Dust therefore represents a serious long term health risk. For this reason, there is strict legislation in some countries limiting the maximum dust level permitted in working areas.

High dust concentration also has a negative effect on working conditions and productivity. The performance of high tech electronics on the TBM can also be affected. Surfaces that are covered in a layer of dust may become slippery increasing the risk of personal injury.

Additionally, high dust concentration can reduce the visibility of drivers and other workers, increasing the risk of accidents.

16.2 Dust control techniques

16.2.1 Ventilation

The quality of the air in the working area should not endanger the safety or the health of the workers. For this reason, proper ventilation should be provided throughout the work place. For dust control, the appropriate dimensioning of the ventilation system is of great importance.

To prevent the dispersion of airborne dust while using TBM's, stone breakers, conveyor belts and at muck transfer points, extraction (suction) ventilation should be installed as close as possible to the points of dust generation. The extracted dust should then be filtered out and deposited through a suitable collection system.

16.2.2 Water spray

Water sprays are also used to help reduce dust. Water spray wets the surface of broken rock, preventing dust formation, as wetted fine particles normally adhere to the rock surfaces. This requires adequate distribution of water spray nozzles on the cutterhead, and a sufficient quantity of water.

In order to minimise dust formation, it is important to ensure that the water spray continuously wets out all the rock surfaces in the breaking process. The timely wetting of rock chips during the breaking process is necessary, as once the dust is airborne, water is relatively ineffective at capturing it. Damp airborne dust may give problems in the extraction ventilation and dust filtration equipment.

One of the other disadvantages of water spray is that the high water jet velocities will create additional air turbulence that can contribute to the creation of more airborne dust.

16.2.3 Foam spray

Foam is one of the most effective ways to reduce dust in hard rock TBM excavation but should always be used in combination with extraction ventilation. The foam is injected through special ports located on the cutter head, and spreads out rapidly to cover whole rock face. The thin films of the foam bubbles wet out broken rock (like water spray), so reduce air born dust formation. Unlike water, foam attracts dust particles and also has strong staying power, forming a continuous matrix in the voids of the excavated rock. This forms a virtual seal which captures and blocks out the dust that would otherwise have become air born on the rock face side.

16.3 Foam application equipment

The equipment is the same as that detailed in 15.5. The cutter head will normally be fitted with a combined system that can provide water or foam. It is necessary to ensure that foam and water are not injected through the same pipes, as this may lead to premature foam breakdown. Also note that the pipe size is different for the two systems.

Tailor made foaming products are available in the market, which offer optimum foaming capacity and foam stability, and in this regard, the requirement on the foaming products are often somewhat different from those used for soil conditioning in EPBM. They should also be bio-degradable, and should not pose a pollution risk to the environment.

ANNEX A: TESTING OF FOAM

A.1 Stability of a foam mixture

1. Introduction

This document outlines a method to measure the stability (half-life) of a foam in its natural state. It should be noted that the actual half-life of the foam is dependent on the soil and other factors such as water content and temperature.

2. Equipment

- A filter – funnel of 1 litres capacity with a non-absorbent filter
- A typical device is available from Schott - Duran or from Pyrex
- A graduated container of 1 or 2 litres capacity made from plastic or non-breakable material
- A 50 ml graduated cylinder
- Retort stand
- A means of making foam with a known expansion ratio (FER) such as a foam generator (described later)
- Weighing balance accurate to 0.1 g
- Stopwatch

3. Materials

- Foaming agent(s) plus any polymers to tested
- Distilled water

4. Test procedure

Make a solution of the foaming agent in the distilled water to a predetermined ratio (typically 3-5%).

For example

97 ml water to 3 g of Foaming agent

Incorporate any polymers following the manufacturers recommendations

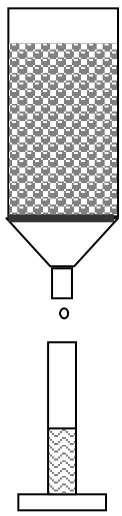
Prepare a foam using the laboratory scale foam generator to the required expansion.

Fill the filter - funnel with 80 g of the foam.

Measure the time for 40 ml of liquid to collect in the lower cylinder (i.e 50% of the liquid content of the mixture).

Record the results of the test.

(The attached Form 2 can be used as a template).



A.2 Stability (Half-life) of a foam/sand mixture

1. Introduction

This test measures the Stability of a foam when mixed with a standard sand at various foam quantities. The test should be used for comparative purposes only as it cannot duplicate the effect of actual soil and TBM conditions. The tests measures how quickly a foam will tend to degenerate when contained in a matrix rather than alone. The test can run for up to 3 days if required with measurements being taken daily or half daily.

It would be possible to replace the sand with soil from the project.

2. Equipment and materials

- A 5 litre heavy duty mixer (Hobart type) with 3 speeds and standard paddles supplied with the machine
- A graduated container of 1 or 2 litres capacity made from plastic or non-breakable material
- A means of making foam with a known expansion ratio (FER) such as a foam generator (described later)
- Weighing balance
- Stopwatch
- Liquid container of either glass or plastic
- DIN Flow table (30cm table) with standard mortar cone
- Calibrated glass or clear plastic cylinder perforated in the base of 1 Litre capacity

3. Materials

- Foaming agent plus polymers if used
- EN 196 standard mortar sand
- Distilled water

4. Method

Weigh 1.5 kg of standard EN 196 sand and add to the mixer bowl.

Add 45 ml of distilled water and mix on speed 1 for 3 minutes.

Prepare the foam as per the half-life test. (Note a fresh sample of foam must be made for each test)

The dilution rates (C_F) should be as per the manufacturer's recommendations although different C_F values can be used.

The expansion rate (FER) shall be 10 unless another FER is required to be tested.

If a polymer is to be added to the mixture the manufacturer's recommendations should be followed.

Prepare for two (2) tests at each foam concentration (C_F).

The quantity of foam (FIR) for each test should be 25g and 50g respectively.

Start the mixer and add the required weight of foam or foam/polymer mixture to the sand during mixing . Mix until the foam is incorporated fully into the sand and a homogenous mixture is obtained. If necessary stop the mix and scrape the excess foam from the mixer blade and bowl sides.

Pour the sand/foam mixture into the perforated glass /plastic cylinder to the 1 Litre mark and level the surface. Note the date and time.

Check the level of the material on a daily or half daily basis over 3 days.

Record the results. (The attached Form 3 can be used as a template).

A.3 Plasticising effect of foam made of foaming agent or polymer

1. Introduction

This test measures the plasticising effect of foam using a standard sand and various foam quantities. The test should be used for comparative purposes only as it cannot duplicate the effect of actual soil and TBM conditions.

2. Equipment and materials

- A 5 litre heavy duty mixer (Hobart type) with 3 speeds and standard paddles
- A graduated container of 1 or 2 litres capacity made from plastic or non-breakable material
- A means of making foam with a known expansion ratio (FER) such as a foam generator (described later)
- Weighing balance
- Stopwatch
- Liquid container of either glass or plastic
- DIN Flow table (30cm table) with standard mortar cone
- Calibrated measure of at least 250 ml for determining the density of the sand and/or sand/foam mixture

3. Materials

- Foaming agent plus polymers if used
- EN 196 standard mortar sand
- Distilled water

4. Method

Weigh 1.5 kg of standard EN 196 sand and add to the mixer bowl.

Add 45mls of distilled water and mix on speed 1 for 3 minutes.

Determine the bulk density of the mixture.

A Flow test may also be carried out if desired using 15 drops of the table.

Return all material back to the mixer or prepare a fresh sample.

Prepare the foam as per the half-life test. (Note a fresh sample of foam must be made for each test)

The dilution rates (C_F) should be as per the manufacturer's recommendations. The quantity of polymer used should be as the manufacturer's recommendations.

The expansion rate (FER) shall be 10 unless another FER is desired to be tested.

Prepare for two (2) tests at each foam concentration (C_F).

The quantity of foam (FIR) for each test should be 25gms and 50gms of the volume of the sand.

Record the results. (The attached Form 2 can be used as a template).

The test shall be completed within 10 minutes of mixing the water and sand.

Note: If the test is to be carried out with soil from the project, first remove all particles greater than 5mm before proceeding with the test.

A.4 Standard Test Report

EFNARC TBM Specification - Standard Test Method

Test Method A.1 - Foam Half Life

Foam Agents:				
Supplier / Manufacturer				
Foam Solution (C_F)				
Date:				
Expansion Rate (FER)				
Start Time				
End Time				

EFNARC TBM Specification - Standard Test Method

Test Method A.2 - Effect of plasticising action of a foam or foam/polymer mixture

Foam Agent				
Supplier/Manufacturer				
Foam Solution (C_F)				
Soil Tested	*EN 196 sand*	*Other (specify)*		
Mass soil/sand (gm)		*Mass water (gm)*		
Bulk Density (kg/m³)				
	Spread in cms after 15 drops on the DIN table			
FER	*10*			
Foam - 0%				
Foam - 25gm				
Foam - 50gm				

EFNARC TBM Specification - Standard Test Method

Test Method A.3 - Foam/Sand mixture Half Life of a foam or foam/polymer mixture

Foam Agents :					
Supplier / Manufacturer					
Foam Solution (C_F)					
Date:					
Injection ratio (FIR)		*25gms*			
Expansion Rate (FER)		*10*			
Initial level					
	Time				
Start Time					
3 days					

A.5 Foam generation in the laboratory

The quality and reproducibility of testing is totally reliant on the quality of the foam produced for the tests. In a poorly produced foam the bubbles combine and break more rapidly and the foam quality varies from test to test.

Methods for generating foam in the laboratory from a foam solution can be classified as :

- By lab scale foam generator
- By high speed stirrer and propeller.

Method 1: Lab scale foam generator

This is the preferred method. The quality of the foam is similar to shaving foam and similar to a TBM machine generated foam.

The lab scale generator should have the capability to generate foams with expansion ratios (FER) between 3 - 20. This can easily be achieved by maintaining a constant liquid volume through the disperser and adjusting the air volume to achieve the FER required.

Difficulties to overcome with this method are a constant and measurable volume of air and a small enough device to limit the volume of foam produced. Measurement of the amount of foam delivered can calculated in litres / minute.

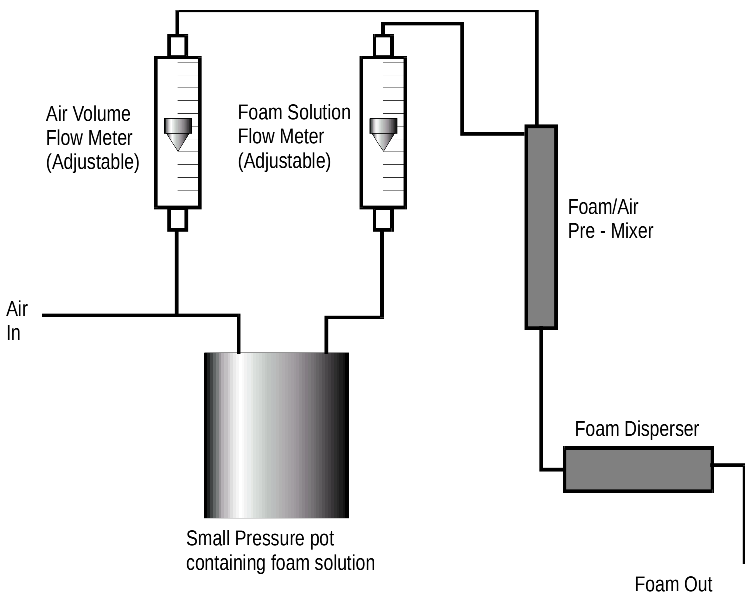
A small pressure pot is used to store the foam solution (C_F). This simplifies the equipment and makes it easier to deliver a constant foam solution rate. The volume of foam solution is controlled by a variable flow gauge.

Compressed air at sufficient pressure and with enough volume is used to both pressurize the pressure pot and provide the flow of air through the gauge. The foam solution and the compressed air lines then feed into a pre-mixer unit where the foam solution and air form a homogeneous mix before going into the disperser where the foam is made.

Using this simple equipment it is possible to produce tens of litres of foam per hour at any expansion ratio and solution rate.

A typical lab scale machine (highly simplified) is shown in the sketch below:

Note: the Pre-mixer is optional.



Method 2: Mixing by High Speed Laboratory Stirrer using a propeller

Although this method cannot be highly recommended, in certain situations it may be the only equipment available.

The method utilizes a high speed stirrer and a propeller type mixing paddle with circular holes in the blades. Revolving at 1500 - 2000 rpm in the solution a reasonable foam can be produced with expansion ratios between 7 - 12.

The volume of foam that can be created at one time is less and the foam is slightly wetter than that produced in a generator. Breakdown of the foam is also more rapid so the foam should not be made until just immediately before it is to be used.

Usually one litre of foam is the maximum that should be made using this method.

Make a solution of the foam agent (plus any polymers) in water to the recommended dilution. Then foam sufficient liquid to a litre of foam depending on the FER required. (e.g 100ml of solution foamed to 1 litre = FER of 10).

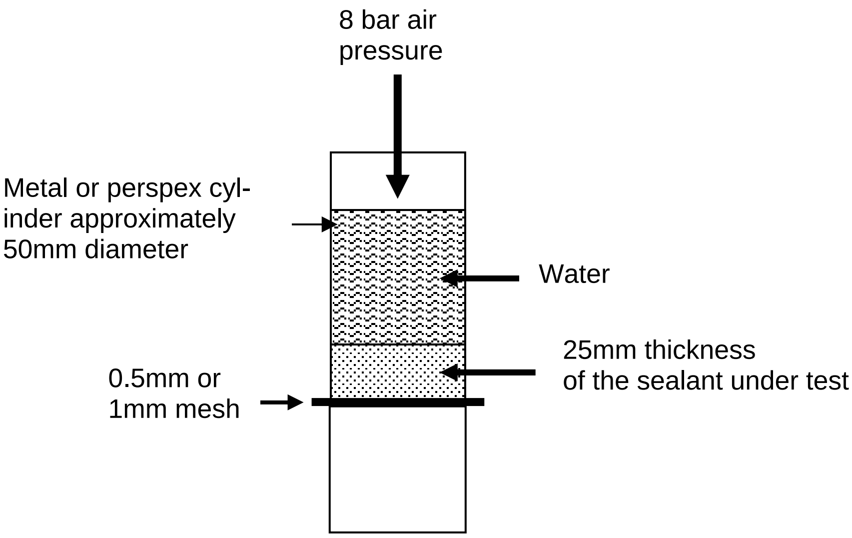
Foaming is best carried out in an unbreakable open top container of volume 1 litre. Add the volume of foam solution for the required FER. Start the mixer and with an up and down movement of the container begin the process of creating the foam. The gentle shaking is designed to both lift the liquid from the bottom and introduce air in the top. Continue until the 1 litre container is full of foam.

ANNEX B: TESTING OF SHIELD TAIL SEALANT

Water Pressure test

The resistance of the sealant to being forced through a wire mesh is determined.

Schematic of the test method.



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