EFNARC

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Specification and Guidelines for the use of specialist products for **Soft Ground Tunnelling**

November 2001

Correction September 2003

EFNARC, Association House, 99 West Street, Farnham, Surrey GU9 7EN, UK
tel: +44 (0)1252 739141 fax: +44 (0)1252 739140 www.efnarc.org

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 industry to make known its comments and views to the European Commission, CEN Technical Committees and other groups dealing with European Harmonisation of Specification 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 firstly for Sprayed Concrete and then for Industrial Flooring. Now it is working to prepare state-of-the-art Specifications for Soft Ground Tunnelling and for Self Compacting Concrete. It is intended that these new Specifications will achieve equal acceptance internationally reflecting the wide scope of technical expertise of its members.

The TBM (Tunnel Boring Machine) Technical Committee was formed at the end of 1998. Its mission was to establish the first European Specification concerning the admixtures and products used in association with the TBM in soft ground tunnel construction, a tunnelling technology increasingly used, but until now not regulated by any national or international standard. Experts in all aspects of tunnelling technology have participated to realise this project.

This document covers the testing and performance of the specialty products used in soft ground tunnelling. It is proposed to develop the scope of the document subsequently to include other aspects of mechanised tunnelling technology, relevant to contractors, consultants, specifiers and machine manufacturers.

This specification was presented for comment and endorsement to an industry workshop at BAUMA 2001 representing material suppliers, contractors and consultants. The need for such a Specification and Guidelines was then confirmed. The feedback received has been taken into account in the preparation of this document. However EFNARC recognises that all specifications must be living documents able to be refined and extended in the light of practical experience and future developments. Comments on this specification are therefore invited and should be sent to EFNARC at the address shown.

Acknowledgements

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

ISBN 0 9539733 2 8

CONTENTS

Amendments
Correction to Table 6.2, 15//09/03

This document comprises Guidelines on the use of specialist products in soft ground 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 a Specification and Guidelines dealing with specialty products and applications used in soft ground mechanised tunnelling, in association with Tunnel Boring Machines (TBM) of the following types:

Slurry or Hydro TBM (STBM)
Earth pressure balance machine (EPBM)

TBM product categories included are:

a soil conditioners
b slurry materials
c annulus back-grouting mortars
d tail seal compound

Structural linings/concrete segments are not included in the scope of the present document. Neither does it cover Hard Rock Tunnelling although certain aspects may be relevant.

2 REFERENCED STANDARDS

EN 197: 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 ISO 13500: Drilling Fluids
ASTM C230: Workability test
Underwriters Lab Test 94: Fire resistance

3 DEFINITIONS

For the purposes of this specification the following definitions apply:

3.1 Annular space
Void between the external part of the lining and the ground.

3.2 Back (fill) grouting
Injection to fill the annular space.

3.3 Confinement
The result of the application of a pressure to the front to keep the ground at given conditions of stability and deformation.

3.4 Earth pressure balance method
Closed shield method with active face support by the pressurised soil.

3.5 Foam
Soil conditioning material made from a foaming solution and air.

3.6 Foaming agent concentration (C_F)
Percentage ratio between the volume of the surface-active agents used and the total volume of the foaming solution.

3.7 Foam expansion ratio (FER)
Ratio between the volume of the foam and the volume of foaming solution used

3.8 Foam injection ratio (FIR)
Ratio between the volume of foam injected at atmospheric pressure and the volume of the ground in place.

3.9 Foaming solution
Mixture of water and surfactant.

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

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

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

3.13 Slurry
Viscous suspension of mineral and/or polymeric products.

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

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

3.16 Tail Seal
Flexible device to prevent water or grout ingress between the lining and the shield.

3.17 TBM (Tunnel Boring Machine)
Machines designed to create/bore tunnels. They perform several functions, from the excavation only to the application of the final lining.

3.18 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.

4 INTRODUCTION TO THE TBM OPERATION

In mechanised shield tunnelling in soft ground, the TBM has several roles to fulfil. Its primary function is to cut the tunnel profile as it is driven forward. In addition it has to stabilise the excavated area and to transport the muck away from the cutting head.

Two different types of TBM are currently used - Slurry Shield Machines (STBM) and Earth Pressure Balance Machines (EPBM). They differ principally in the method of stabilising the excavated area. The STBM achieves this by means of a Bentonite or polymer slurry which is injected at the cutting face and forms a mud cake to stabilise and seal the open face of the tunnel. With the EPBM the pressurised excavated ground itself is the support medium for the tunnel face.

The two types of TBM are shown schematically in Figure 1.

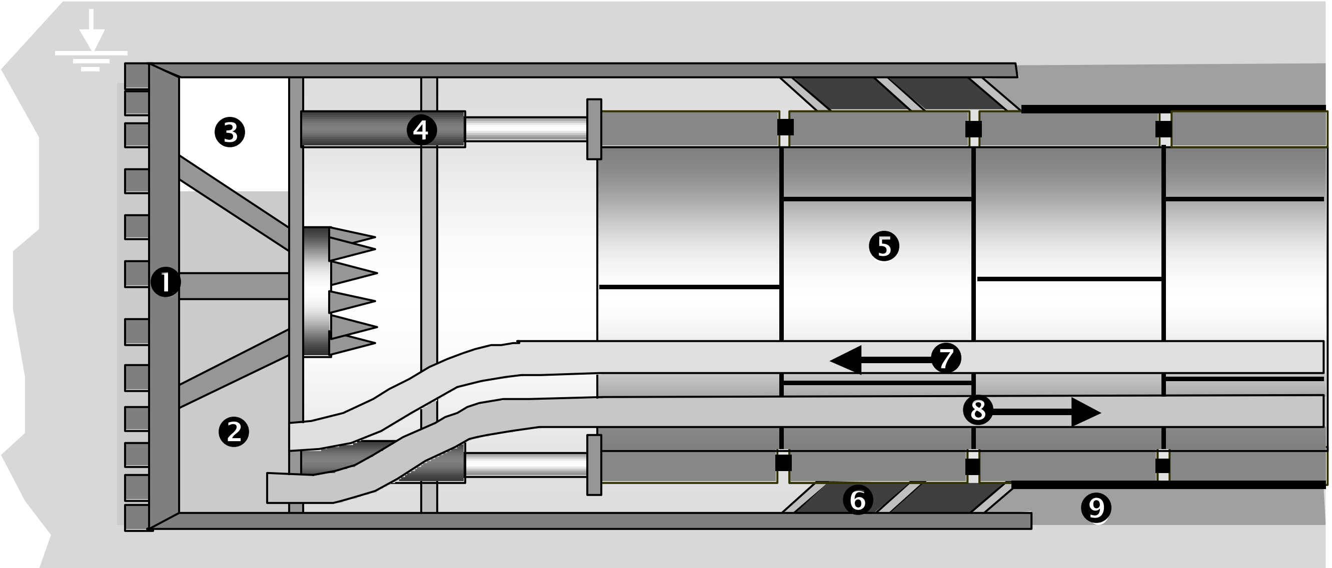
The selection of the method to use in a particular situation will depend on a number of factors.

The Earth Pressure Balance method can achieve high drive rates and requires less back-up plant, but is limited in the types of ground in which it can operate.

The Slurry Shield method is more versatile and can operate in a much wider variety of ground conditions. However an extensive separation plant is necessary to process and re-cycle the bentonite slurry and there is a greater volume of muck requiring costly disposal in an environmentally friendly way.

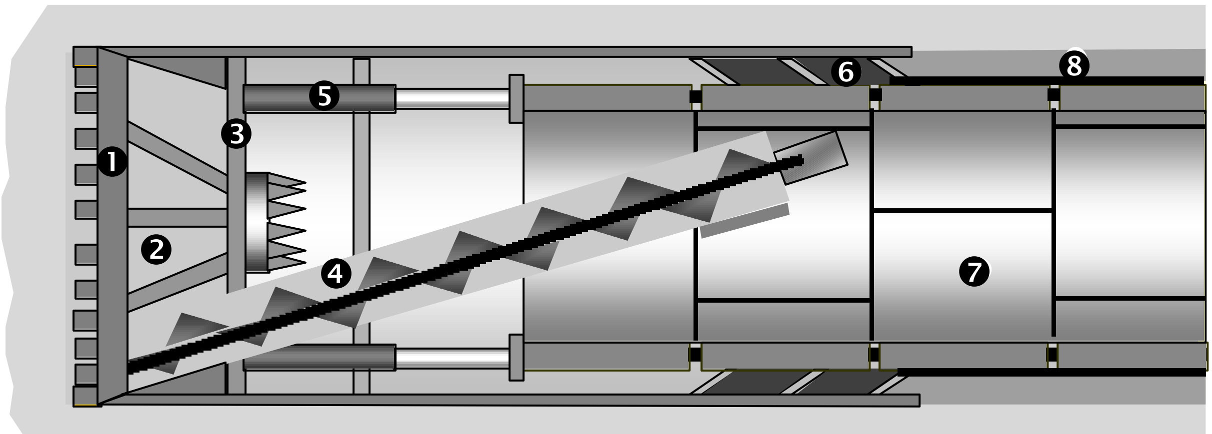
Figure 1: Schematic representation of STBM and EPBM machines

Slurry Shield Tunnel Boring Machine



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

EPB Tunnel Boring Machine



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

5 SOIL CONDITIONING

5.1 General

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

Tunnel building for infrastructure projects (subways, sewers, water supply, etc) often takes place in soft and wet 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 (STBM) and the earth pressure balance machines (EPBM), such risks have been reduced.

But even the most advanced tunnel machine will face problems in mixed and changing ground conditions which it cannot master safely. Instead of costly changes and adaptation of the machine, even if possible, it is simpler to treat the ground to provide properties which the machine can handle.

With the Slurry Shield 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 machine cutterhead and also acts as an aid to soil transportation by pumping.

With the EPBM technique, soil conditioning products are generally injected ahead of the cutterhead and often also into the working chamber and screw conveyor. By correctly choosing and adapting this material and its recipe to the encountered soil and ground water conditions, it can:

- reduce stickiness of plastic clays (that can lead to blockage of muck conveying) by both TBM with or without shield
- lower angle of internal friction and abrasiveness of the soil slurry (in order to reduce power for soil extraction and conveyance and wear costs)
- create plastic deformation behaviour (an even and controlled supporting pressure increases the stability of the face and reduces segregation and 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 STBM - makes the on-site muck handling easier with more traditional means and eliminates the need for a sophisticated separation plant.

5.2 Geotechnical considerations

Level of investigation

The excavation of a tunnel may cause many changes in the original soil structure, such as modifying the existing stress status, to produce deformations. The reaction of a soil to the excavation depends on the geological and geomechanical characteristics of the soil and on the excavation and reinforcement methods. Therefore a detailed knowledge of these characteristics, obtained from geological, hydrogeological and geotechnical preliminary studies, is necessary in order to select the appropriate construction method and dimensioning. This will determine the tunnel layout and geometry to help minimize the risks of tunnel instability and the modification of the surrounding environment.

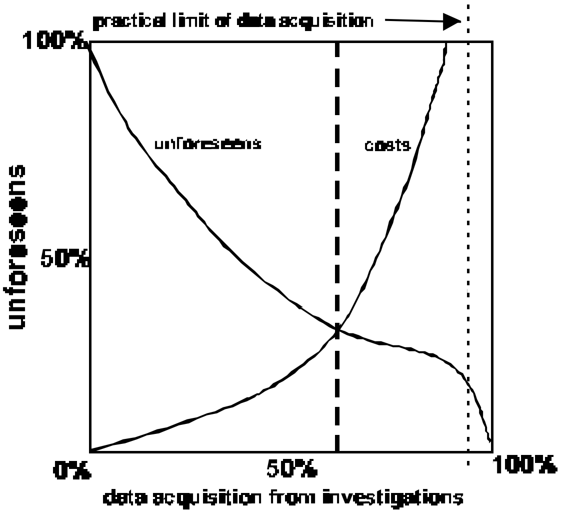
The amount and details of the site investigation will depend on the dimension and purpose of the tunnel, on its location and on the ground conditions and existing knowledge. The greater the volume of data acquisition, the lower will be the risk of uncertainties.

The relationship between the level of investigation and the level of risks and costs is illustrated in Figure 2.

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 2: Risk/data acquisition balance

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



Design phase
First of all, those in charge of the study have to collect 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 environments.

To optimise the geometry and layout of the tunnel, the following parameters have to be taken into consideration:
- the nature of the soil in the path of the tunnel (morphology, mechanical characteristics, deformability, etc)
- the position of the different layers (stratigraphic characteristics)
- the direction of the main discontinuities (tectonic-structural characteristics)
- the presence of water (hydrogeology)
- the nature and highness of the cover
- the impact of the excavation on the environment (soil stress, subsidence, hydrogeology alteration)
- buildings, traffic systems, presence of pipes and services at the surface.

Generally some geological maps or studies are 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
- georadar

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

The geotechnical study, together with the geological and hydrogeological studies, should allow for:
- determination of the conditions of stability
- dimensioning of the reinforcement and the tunnel lining properties
- identification of the geotechnical classification of all present materials
- 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

Soft Ground

In the specific case of tunnelling in soft ground, the following investigations should be performed:
- soil identification
- determination of the initial stress conditions
- study of mechanical characteristics
- study of the hydraulic characteristics

Soil identification
The main parameters to be identified are:
- density, wet and dry
- water content
- grain size distribution
- pore volume
- abrasiveness (grain shape and hardness)
- Atterberg limits (when clay is present)
- mineralogical analysis – where relevant
- elastic modulus and Poisson ratio
- cohesion
- permeability
- angle of friction
- undrained shear strength

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

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, 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.

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 performed a detailed hydrogeological study and thus to know the soil permeability, expected water pressure, direction of the current, seasonal and tidal variations, development of groundwater reservoirs, etc. To determine the soil permeability, laboratory tests on samples are not sufficient and field tests are necessary.

Geotechnical Design Report

The geotechnical design 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 of different type of soil
- potential change of the ground properties with compressed air

Environmental impact

A tunnel excavation may affect the environment equilibrium.
The following risks have to be considered.
- subsidence, particularly dangerous in urban area
- structural damages due to vibrations
- alteration of the original hydrogeological situation, which can induce further subsidence
- water pollution

5.3 Slurry shield

5.3.1 General

This 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. The limits of its utilisation are linked to the formation of a Mud Cake and to the granulometry of the ground to be excavated.

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 aggregates of soil even with a very low cohesion.

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, and 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 then require to be treated 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 which is formed by impregnation of the slurry 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 for the pressure to be maintained. Generally, as more water is expelled from the slurry, so 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 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.

5.3.2 Products

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.

5.3.3 Performance requirements

When excavating with a Slurry Shield TBM (STBM), 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 suspend the cuttings, but it also acts to maintain pressure, to lubricate and cool the cutting head, and to reduce abrasive wear of the cutting tools.

The technical specification 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.

5.3.4 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.

5.3.5 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 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 then to obtain the most complete mechanical disintegration of the particle conglomerates 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 then of main concern 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 later introduction of these chemicals.

5.4 EPB Tunneling

A modern EPB 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.

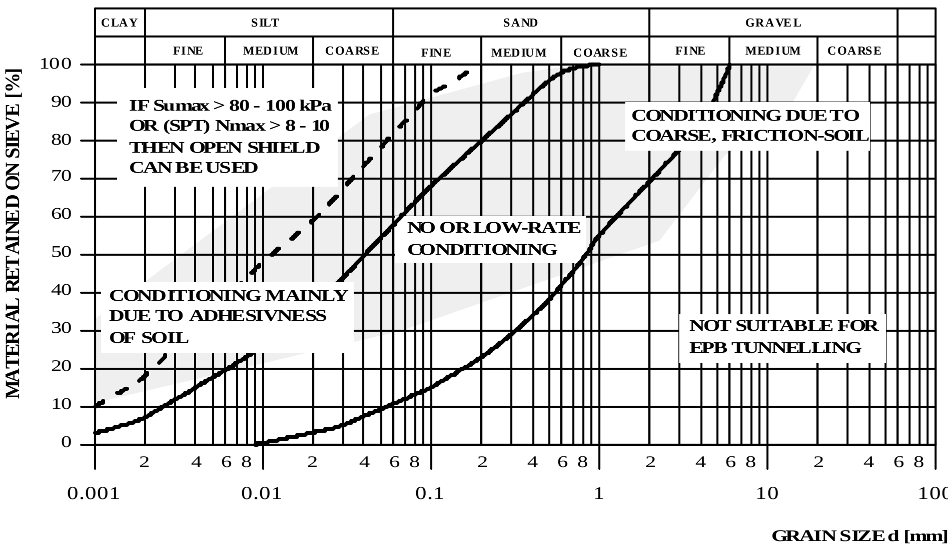
The control of face support is a major issue in EPB shield tunnelling. Continuous support of the tunnelling face must be provided by the excavated soil itself, which should completely fill the working chamber. The required support pressure at the tunnelling face will be achieved through:
- thrusting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

5.4.1 Geological requirements

Figure 3, which indicates typical particle size distributions for the use of EPB Tunnel Boring Machines, can be used as a guide in order to give an idea of the limits of EPB TBM. It indicates also in which cases soil conditioning might be possible or necessary. However the information should be taken as no more than a guide, as there is increasing practical experience of EPBMs operating in coarser soils up to 20 – 40 mm.

Figure 3: Limits for EPB – tunnelling
(figure taken from "Advances of soil conditioning in shield tunnelling", Jancsecz, Krause & Langmaack, ITA 1999, Oslo)



5.4.2 Products used for EPB Tunnelling

EPB 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. Other types of additives are special dispersing agents to avoid clogging problems, anti abrasion additives for the cutterhead and its tools as well as for the extraction screw. In addition bentonite and other additives are also being used to avoid segregation and reduce the permeability of the soil. Water may also be used in some circumstances.

5.4.3 Performance Requirements

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

- foam:
  maintenance of pressure, fluidising effect for the soil, creation of an homogeneous soil paste, permeability reduction, lowering of torque, dispersing of clay, reduction of abrasion;
- dispersing agents:
  mainly 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;
- bentonite, or similar fine particles:
  addition of fine particles to soils with lack of fines, support for polymer and foam, to use for maintenance and repair works.

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

5.4.4 Conditioning requirements

The purpose of conditioning additives is primarily to maintain the necessary support pressure in the working chamber. They will also reduce torque and abrasion, and assist with the transport of the muck.

The key parameters involved are:

- C_F - concentration of surfactant agent in water (→ foaming solution)
  $C_F = 100 \times m_{\text{Surfactant}} / m_{\text{Foam Solution}}$
  $m_{\text{Surfactant}}$: mass of Surfactant in Foaming Solution
  $m_{\text{Foam Solution}}$: mass of Foaming Solution

- FER - Foam Expansion Ratio
  $FER = V_{\text{compressed air}} / V_{\text{Foam solution}}$
  $V_{\text{compressed air}}$: Volume of compressed air
  $V_{\text{Foam solution}}$: Volume of foaming solution

- FIR - Foam Injection Ratio
  $FIR = 100 \times V_{\text{foam}} / V_{\text{soil}}$
  V_{Foam}: Volume of Foam (at 1 atm)
  V_{Soil}: Volume of in situ soil to be excavated

The Foam type chosen should match the properties of the soil to be excavated - see figure 4.

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.

Figure 4: Definition of EFNARC Foam types for EPBM relative to different soils

	EFNARC Foam types			**Foam Injection**		**Other tunnel additives**		
Soil	A	B	C	c_F	FIR	dispersing agents	foam stabilisers	soil stabilisers
Clay				**+**	**+**	**++**	**-**	**-**
Sandy clay – silt				**+**	**+**	**+**	**-**	**-**
Sand – clayey silt				**+**	**++**	**o**	**+**	**-**
Sand				**++**	**+++**	**-**	**++**	**++**
Clayey gravels				**++**	**++**	**-**	**+++**	**+**
Sandy gravels				**+++**	**+++**	**-**	**+++**	**+++**

- generally not necessary

o not generally necessary, but sometimes useful

\+ useful in low quantities

++ useful in increased quantities

+++ strongly recommended in increased quantities

NB other soil conditions may exist which affect the suitability of different foam types.

5.4.5 General parameter set for soil conditioning:

- Foaming solution
  The concentration of foaming solution C_F is typically in the range 0,5 - 5,0%, in most cases around 3%, but should follow the manufacturer's recommendations. This concentration strongly depends on the amount of water which is injected to or which is already present in the soil and furthermore depends on the activity and stability of the used tunnel foam.
- Foam Expansion Ratio FER
  The FER should be at 5 – 30, in most cases around 10. 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.
- 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 play an important role.
- Polymer addition
  In some cases polymers can be added to improve foam stability or adjust the consistency of the soil passing through the working chamber or screw conveyor. A typical example might be in wet, sandy soils with little cohesion. The used concentration should be 0.1 – 5.0% in the foaming solution but can also be injected directly in their undiluted version.
- Stabiliser addition
  These additives should mainly prevent segregation and its related effects (decreasing face stability, clogging, etc) in the working chamber. Their concentration should be 0.1 – 5.0% in the foaming solution

Other additives: The concentration of other tunnel additives like anti-abrasion or anti-clogging products cannot be given in general because this strongly depends on the additive type and function.

Note: In practical situations the volume of Foam will be reduced according to the level of overburden pressure.

5.4.6 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 could prove the true efficacy of such products. This arises because currently there are no tests available which will allow the full simulation of soil and foam under conditions of pressure, to assess what effect that has on face support, mixing and transportation of the soil from the face.

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 provide comparative testing is first carried out.

Typical 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.

5.4.7 Test methods for conditioned soil

At present, soil conditioning in soft ground tunnel boring machines remains very much a “black art”, determined largely by experience or trial and error. This is no implied criticism but represents the reality in the industry where there has been little formal research into the key parameters. This applies as much to the selection of the appropriate foam and polymer products as to their application.

The purpose of this specification is to make it possible for a Contractor to apply a series of standard tests to the soil from the project and to have a clearer idea of how to begin and what and when to change products or dosage levels before starting the drive.

The testing of soil can usually only be carried out at atmospheric pressure but, in practice, the soil at the face and in the working chamber is at a variable pressure depending on circumstance. We also know that ground conditions change or can change frequently, more on some projects than others.

This presents an enormous challenge and poses key questions. How can the testing be realistic in the face of so many variables? Will the testing provide sensible and practical results?

There are no tests that exist at general laboratory-scale level that can simulate the effect of foam or polymer with a particular soil under pressure. Therefore, until such time as alternatives can be developed, it is necessary to work with the known test methods for soil and apply the same tests to the soil after conditioning.

Proposed Test Methods

- Mixing Method
- Cone Penetrometer Test (BS EN1377 or NF P94-051)
  - determination of Fluidising effect of additives on fine soils (clay/silts)
- Slump Test using a standard Concrete test method
  - determination of Fluidising effect of additives on coarse soils (sands,silty sands)
- Shear tests (Simple Shear Box)

- determination of the change in internal friction before/after modification with a foam solution

- Torque tests
  - Vane Test on material passing 5mm sieve with foam

Because of the wide variety of soils that will be encountered and the wide range of potential operating conditions it is not possible at present to define minimum levels of performance for the conditioning. However experience accumulated in operating these tests will hopefully lead towards such a development.

6 Shield tail sealant

6.1 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:

excellent resistance against:
- water wash-out
- wear
- flowing-off / extrusion
- mechanical pressure

good pumping properties over a wide range of temperatures
good wetting characteristics
strong adhesive properties
good stability (no fluid separation) in storage and under pressure
low toxicity and be environmentally friendly

6.2 Performance characteristics

Characteristic	*Class A*	*Class B*	*Class C*
Water Resistance to 8 bar for 5 minutes (test method – Annex B.2)	*Pass 1.0mm mesh in >5 minutes*	*Pass 0.5mm mesh in >5 minutes*	*Pass 0.5mm mesh in <5 minutes*
Slump test (test method – Annex B.1)	*< 30 mm @ 20° C*		
Self extinguishing to fire (test to Underwriters Laboratories 94)	*Less than 5 minutes*	*5 - 8 minutes*	*More than 8 minutes*
Percentage weight loss after fire test	*<3%*	*<10%*	*>10%*
Flash point	*>200°C*	*150 – 200°C*	*-*

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

7 Annulus grouts and mortars

7.1 General

This specification 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 specification 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 specification 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.

7.2 Background

7.2.1 Engineering 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.

7.2.2 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.

7.3 Constituent Materials

7.3.1 Cement

The cement shall conform to EN 197.

7.3.2 Fine Aggregates

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

7.3.3 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 .

7.3.4 Admixtures

Admixtures should conform to EN934 Parts 2,5,6 where relevant. However, non-standard admixtures may be used after tests to confirm their suitability.
The use of admixtures falls into various categories :

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

7.3.5 Additions

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

7.3.5.1 Hydraulic

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

7.3.5.2 Non-hydraulic

- Limestone powder
- Finely divided quartz flour
- Bentonite

7.4 Annulus grouting method

Grouting can be carried out :

- Through channels in the tailshield 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:

7.4.1 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.

7.4.2 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.

7.5 General grout requirements

7.5.1 Types of grout

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

a) Active
b) Semi-inert
c) Inert

- 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/m^3
- 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/m^3 Portland cement. But essentially the grout may take a considerable period of time to harden although stiffening will occur more quickly.
- 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 or the need for waterproofing.

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.

7.6. Characteristics

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

a) In the short term the grouting procedure shall prevent settlement prejudicial to the safety of the environment

b) 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.

7.7. Performance Requirements.

All grouts shall have the following essential requirements:

7.7.1 Plastic Consistency for 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*

7.7.2 Plastic consistency requirements for two-component grouts

The two components 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:

i) a mortar consistency Component A with a liquid Component B
ii) a liquid consistency Component A with a liquid Component B

For i) The Component A should have the properties described above 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.

For ii) both Component A and Component B are generally high fluidity products. In this case Component A should still match the requirements of the table above 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 millimeter 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.

7.7.3 Hardened Properties

The hardened properties, for example strength, 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.***

7.8 Specification for Grouting Equipment

7.8.1 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.

7.8.2 Mixing

7.8.2.1 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.

7.8.2.2 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 flowmeter. 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 flowmeters 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.

7.8.2.3 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.

7.8.2.4 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.

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.

7.9 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.

8 Declaration of Conformity

8.1 General

This applies to product supplied in accordance with this specification.

8.2 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.

8.3 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.

9 Quality control

The manufacturer shall operate a quality control 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 not less than once per year. If any non-compliance with the requirements of EN ISO 9000 is found, the certification body shall either:

(i) require correction of non-compliance within a stated time which, if not carried out, shall result in withdrawal of the certificate, or
(ii) immediately withdraw the certificate, if correction is not possible.

10 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 regulations

In addition the following information shall be made available before use:
h) instructions for storage and use
j) material safety data sheet

11 Environment/Health & Safety

The tunnelling operation and the method of application of all associated products should meet all health, safety and environmental regulations valid to the place of use. Prior to commencement of any contract a full risk assessment and safety plan should be established and approved by the Client in conjunction with the Project Engineer.

Generally the Risk Assessment should cover the proximity of wells, aquifers or other water sources used for human consumption, this includes factors such as flow rates of water through the ground.

The environmental effects of the proposed admixtures or additives should be assessed. This will include biodegradability, toxicity and bio-accumulation testing.

It is the responsibility of the manufacturer to show that the products supplied have formal certification to meet the local environmental regulations.

ANNEX A: Testing of Foam

A.1 Stability of a foam mixture

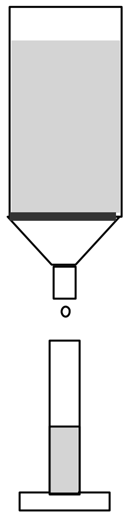
1. Introduction

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

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



3.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 Liter capacity

Materials

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

3. 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

Materials

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

3. 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 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 Admixture :				
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 Admixture				
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 Admixture :					
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.

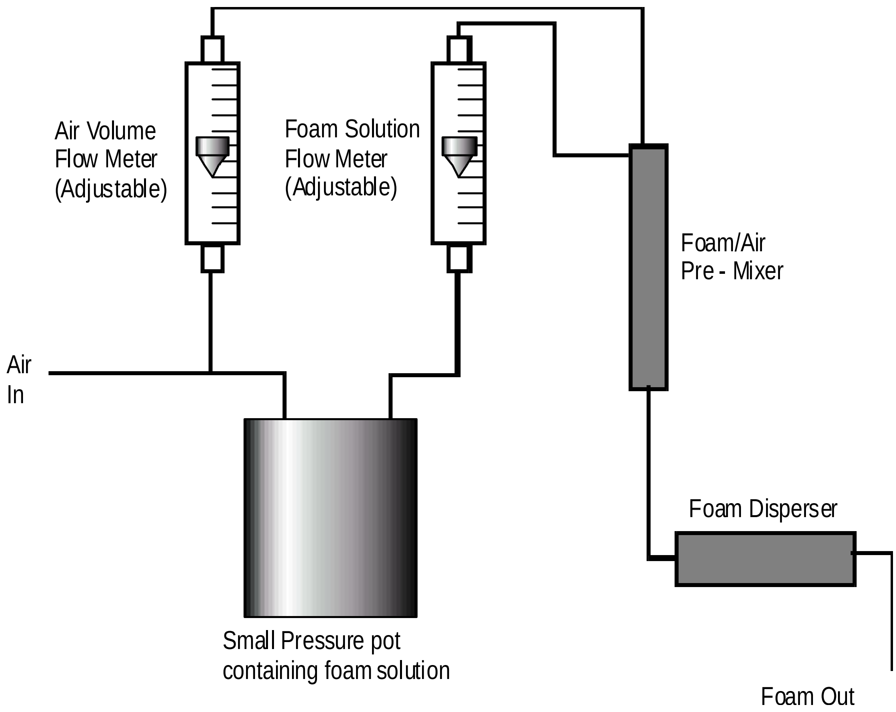
Difficulties to overcome with this method are a constant and measurable volume of air and a small enough device to limit the volume of foam produced. Measurement of the amount of foam delivered can calculated in litres / minute.

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 and into the disperser where the foam is made. Before this is a mixer unit to ensure the foam and air mix properly.

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 Premixer 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 a 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.

One method is to foam sufficient liquid to a litre depending on the FER required. (e.g 100ml of solution foamed to 1 litre = FER of 10).

Into an unbreakable open top container of 1 litre add the required volume of foam solution.
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 required volume of foam is created and the consistency of the foam appears constant.

ANNEX B: TESTING OF SHIELD TAIL SEALANT

B.1: Slump test

Scope

A simple test to characterize the adhesion and slump of a TBM shield tail sealant, when it is in contact with metallic surfaces.

Method

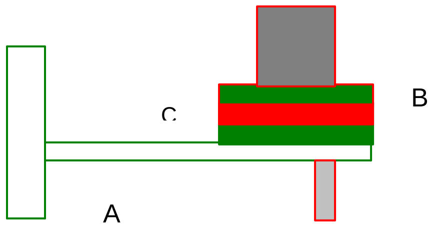
Place the support « A » horizontally. Spread the sealant «C» on the steel plate to obtain an homogeneous layer of about 2-3 mm of thickness. Then place the upper plate « B » on the sealant layer and put a load of 2 kg on top for 2 minutes. Take off the load and raise the support into a vertical position.

One minute later, measure the vertical movement of the 'upper plate' « B ».

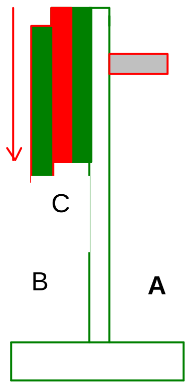
Sample temperature should be 20 to 25 °C (unless different requirements are requested).

Schema of the equipment :

Horizontal position



Vertical position



The plates have dimension of 100 x 100 x 10 mm and their weight is 285 g.

B.2: Water Pressure test

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

Schematic of the test method.