LUBRICATION AND SOIL CONDITIONING
IN TUNNELLING, PIPE JACKING AND MICROTUNNELLING

A STATE-OF-THE-ART REVIEW

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August 2000

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STATE-OF-THE-ART REVIEW

1. INTRODUCTION

1.1 Reasons for soil conditioning and lubrication

Lubrication and soil conditioning are being increasingly used to improve the performance of tunnelling, pipe jacking, microtunnelling and horizontal directional drilling (HDD). The lubrication and conditioning may be effected by the addition of suitable agents at various points throughout the tunnelling process, such as: at the point of cut in the tunnel face; within the cutter head; in the muck removal system; around the outside of the tunnelling shield and/or the pipes in a tunnel or pipe line formed by pipe jacking or microtunnelling; in the separation units of a slurry system; or to muck on its way to tip. This improvement may come about in a number of ways which are discussed in detail in section 2 and summarised here:-

- reduced wear of machine cutter head face plate and tools, and all wear parts of the muck removal system
- improved stability of tunnel face, with consequently better control of ground movements
- improved flow of excavated material through the cutter head
- reduced cutter head power requirements
- reduced friction and heat build up in shield
- excavated material formed into a suitably plastic mass
- enhanced properties of soil in the pressure chamber of earth-pressure balance (EPBM) machines, leading to:-
  - more uniform pressures in the working chamber
  - better control of groundwater inflow by reducing permeability
  - reduction in clogging of machine head chamber
  - more controlled flow of soil and water through the screw conveyor
  - easier handling of excavated soil
- support of excavated bore in pipe jacking, microtunnelling and HDD
- reduction of jacking forces in pipe jacking and microtunnelling
- reduction in the friction losses in the pipes, valves and pumps of a slurry machine system
- better separation of spoil from slurry in a slurry machine system
- more acceptable spoil for disposal
- through a number of the above, improved safety for personnel working in the tunnel, particularly during cutter changes and cutter head inspections.

1.2 Purpose of this review

In many cases it will be the intention to achieve several of the benefits listed above. However the various materials employed may interact with each other and with different types of soil in a complex manner. Practical experience to date has been mixed, with significant success in some cases and negligible or negative effects in others. In this report an attempt is made to establish the aims of lubrication and conditioning, review the materials available, promote understanding of their mode of operation and hence most effective usage, and provide lessons from practical experience of their use on a number of projects. The intent is to promote the correct application of appropriate lubrication and soil conditioning as successful and cost effective techniques.

The use of lubrication and soil conditioning is developing rapidly in various parts of the world, and those who have used it successfully may (for good commercial reasons) be unwilling to disclose all their hard-won knowledge. Hence the review can not hope to be complete and will in time become out-of-date. Nevertheless it should help to establish the current state of knowledge, provide a common base of information for engineers working for clients, consultants and contractors, and encourage consideration of the use of the methods *at the design stage* rather than as remedial action once problems have occurred.

While some test methods have been developed and some basic research undertaken in relation to lubrication and soil conditioning in tunnelling and pipe jacking, there is still much that needs to be done to establish the most effective procedures and allow comparisons to be made of the performance of different materials in various situations. Areas requiring further development are highlighted, with the intention of encouraging appropriate research both in the laboratory and under field conditions.

2. USES OF LUBRICATION AND SOIL CONDITIONING

2.1 Methods of tunnelling and pipe jacking

Since the uses of lubrication and soil conditioning vary with the different types of tunnelling technology, it is necessary first to review briefly the methods in current use. Any tunnelling activity essentially involves three operations: excavation of the tunnel bore through the ground, with the minimum of disturbance to the ground ahead of the face and around the tunnel; removal of the excavated material from the tunnel and its subsequent disposal; and provision of a tunnel lining. The excavation methods considered here all use tunnelling machines; soil conditioning is not appropriate for 'open face' excavations such as in 'drill and blast' or NATM-style tunnelling. In highly stable ground, excavation in large diameter tunnels may be by backacter, while for short drives of small diameter, hand excavation with clay-spades may be the most economic. A third alternative is the use of an open-face tunnel boring machine with a rotating cutter head.

In less stable ground, such as softer clays, cohesionless soils or highly fractured rock (particularly below the water table), the face must be supported while excavation proceeds. This can be done in one of four ways: by mechanical support from a closed machine head through which excavated material is extracted at a controlled rate as the shield advances; by compressed air pressure; by pressure from a fluid, usually either a bentonite slurry or a slurry formed from water mixed with some of the excavated spoil; or by pressure from excavated material within the working chamber of the shield. The effectiveness of compressed air in fractured rock is highly questionable and caution should be exercised. The last two types are usually referred to as a 'slurry machine' and an 'earth-pressure-balance machine' (EPBM) respectively (Figure 1). One development of the slurry shield, known as a 'hydroshield', employs an air bubble within the machine head. This provides a 'cushion' in which the pressure can be much more accurately controlled than in a pure slurry or EPB shield, and which helps to maintain a reasonably constant support pressure with variations in the rate of advance of the cutter head and of removal of the spoil (Figure 2a). A number of machines have also been designed to work in two or more of the possible modes, ideally with conversion between the modes able to take place underground to cope with changing ground conditions.

Methods of removing the excavated material depend on the method of excavation and the conditions of the spoil. In a slurry shield the excavated material is transported away from the face to the ground surface in the supporting slurry; the spoil is then usually separated from the slurry so that the slurry may be re-used and the relatively clean spoil taken to tip. Large particles (cobbles and boulders) may be broken down, to a size suitable for transport through the slurry pipes, by a crusher unit either in the head chamber in front of the discharge point or in the discharge line close to the head chamber. In EPBM shields the spoil is extracted from the pressure chamber by a screw conveyor and removed in muck wagons or by a conveyor system. Very soft soil may be extracted by pumping, and pneumatic transport systems have also been used. Similar means may be used with open face machines or shields employing mechanical support. Typical arrangements are shown in Figure 2b.

Microtunnelling systems use one of two technologies. The first is essentially a scaled-down slurry shield system; the second extracts the excavated material by an auger screw, with the cutter head driven via the shaft of the screw. Horizontal directional drilling is increasingly being used for small-diameter installations; it uses similar technologies to vertical drilling, with air, foam, water or slurry flush to remove the cuttings (Lyon 1999a). A pilot hole is drilled, and the service pipe installed by pulling back with the drill string; the diameter may be increased by over-reaming at the same time.

Lining systems for shield-driven tunnels most commonly employ segmental rings of precast concrete or cast iron, constructed within the tail of the shield. Some systems have been developed to allow the casting of a lining of *in situ* concrete, though this is more commonly used for a secondary lining. In pipe jacking and micro-tunnelling the lining consists of a 'string' of complete pipes pushed forward from the launch pit by hydraulic jacks; the shield may be pushed forward along with the pipes, or may have its own jacks allowing it to be jacked forward by reacting against the lead pipe; the pipe string is then closed up behind the shield. Pipe jacking is the only really practical method for small diameter pipes, of diameter less than 900mm, when it is commonly referred to as microtunnelling. It competes with segmental linings in the range of diameters between about 1.5 and 3.0m. Jacking methods may also be used for large cross-sections of rectangular or other complex shape over relatively short distances, such as beneath existing railways; this is known as tunnel or box jacking.

2.2 Choice of shield type

In many cases a choice will arise as to whether a soft-ground tunnelling machine should be a slurry or EPB shield type. Slurry machines may be used in a wide range of soils, as shown in Figure 3a. Hydroshields increase the range somewhat further by improving control of face pressure and ensuring stability in coarser-grained soils (Figure 3b). EPB shields are only effective in natural ground with a reasonably high fines content, above line 1 in Figure 3c, and sufficiently high water content for the remoulded soil after passage through the machine to be soft, plastic and 'pulpy'. EPB shields were originally developed during the 1970s in Japan, where the ground conditions encountered were often close to ideal. For other types of ground the soil must be conditioned by additions of water, clay or other agents to provide the required consistency for the machine.

Kusakabe et al (1999) present a useful table from the Japanese Society of Civil Engineers Standard Specification for Tunnels, reproduced in Table 1, comparing ground conditions in which either slurry or EPB shields may be used. Without additives (soil conditioning agents), the use of EPBMs is limited to relatively soft and fine-grained soils, while slurry machines may be used in all soils except for those containing boulders too large or too numerous to be handled by the machine. However slurry machines introduce the extra demands of separation plant, and separation of fine grained soils may be difficult and expensive. Face stability may also be hard to achieve in coarse granular soils below the water table. With suitable additives, EPBMs may be used in the full range of soil types, including those with large boulders, though Maidl et al. (1996) suggest that soils with grading between curves 2 and 3 in Figure 3c are not suitable under high water pressures and those below line 3 are too permeable to be treated with conditioners even above the water table. Steiner (1995) considered that in glacial soils with a wide range of gradings, effective operation of an EPB shield without additives required that the soil had a liquid limit in excess of 30%. Improvements in conditioning agents and their application have gradually extended the range of treatable soil types.

Maidl et al. (1998) summarised the requirements for conditioning in relation to the same three particle size distribution curves (Figure 3c) as :-

1. Fine grained soils with liquidity index in the range 0.4 to 0.75 - add water and clay plus polymer or tenside (surfactant) foam;
2. Permeability less than 10^{-5} m/s, water pressures less than 2 bar (200 kPa) - add clay and polymer or polymeric foams
3. For more permeable soils and/or higher water pressures - use high density slurry, high molecular weight polymer suspensions, polymer foams.

They consider that the introduction of foam conditioning agents has been one of the major technical developments in tunnelling in Europe in recent years, and that there is still considerable potential for further development.

Lubrication and soil conditioning agents may be introduced at various points through a tunnelling system, from the face excavation to final disposal of the spoil. These applications are summarised in Table 2 and Figure 4 and discussed briefly in the sections below.

2.3 The tunnel face

In all types of machine, provision of a lubricating agent which reduces the friction between soil cuttings, and between the cuttings and the cutters and cutter head, will reduce power requirements for any particular advance rate and also wear on the machine. Reducing power has many secondary effects apart from the obvious reduction in energy costs. For instance the build up of heat, which may be difficult to dissipate in some ground conditions, will be slowed. Lower torque on the machine head will reduce distortion of the shield and extend the life of seals and bearings, which are some of the most critical and vulnerable components in the machine.

To be fully effective, the lubricating agent must be added at the point of cut, before remoulding of the cut soil starts. Injection into the working chamber (see next section) may be too late to provide the full potential benefit. Early addition is necessary to allow sufficient mixing time with the soil, even if the benefit being sought is not required until later in the tunnelling process. Lubrication at the cutters nearest to the periphery of the cutter head, where relative soil/cutter velocities are greatest, is particularly important. Water or slurry introduced as high pressure jets may assist with cutting the soil.

In a slurry machine, fluid pressure in the head is used to support the tunnel face. In clay soils the slurry may consist of water with a proportion of suspended clay from the excavated material which is not completely removed at the separation plant. In more permeable soils a filter cake must first be formed in the soil face to prevent the slurry from dispersing into the ground; a bentonite slurry is then normally used. Bentonite on its own may work satisfactorily in silty or sandy soils, but in coarser soils additional materials may be included to increase the slurry density, promote the formation of a filter cake and reduce slurry loss into the ground, mainly by increasing the amount of material capable of blocking pore spaces.

It is possible that inclusion of foam in the slurry may provide similar benefits to the air cushion in a hydroshield system. This could be of particular application in microtunnelling machines operating on the slurry system.

Earth pressure balance machines support the face with pressure from the mass of remoulded soil within the machine head chamber and screw conveyor. Beneath the water table, this can only be done if the soil is not too permeable, otherwise the water pressure cannot be resisted. It is generally reckoned that a coefficient of permeability of less than 10^{-6} to 10^{-5} m/s is needed for an EPBM to function satisfactorily; in more permeable soils, it is possible that conditioning agents may permeate the face a short distance ahead of the machine and reduce the permeability to an acceptable level.

2.4 Machine head

Two aspects of soil conditioning in the machine head chamber are again common to all types of tunnelling machine: reduction of friction and hence wear within the head; and prevention of clogging from the recompaction of plastic clays and their sticking to surfaces within the head. The former results from lubrication of the soil cuttings and the machine surfaces; the latter by separation of the clay cuttings in open TBM or EPBMs and effective dispersion of the cuttings in the slurry of slurry shield machines. However the greatest actual and potential use of soil conditioning is in EPBMs, in controlling permeability and producing spoil in the head chamber of a suitably plastic consistency to allow satisfactory pressure balance to be achieved at the face.

EPBMs were first used in soft, sensitive clays, silts and fine sands, which on remoulding in the machine head readily produced a mass of soil of soft and ‘pulpy’ consistency of low permeability, with at most the addition of a small quantity of water. They were not considered suitable for use in very stiff clays, in which open face TBMs were used, with compressed air to control water inflows when more permeable soils were encountered; nor in sands and gravels, which were too permeable and could not form a plastic mass, where slurry shield machines became the norm.

However EPBMs have many potential advantages. They do not require the separation plant needed for a slurry system; it is often difficult to determine the best treatment plant layout in advance since the grading of the excavated material is not known precisely. It is not always possible to stabilise a face in cohesionless soil below the water table with a slurry machine, and catastrophic collapses are possible; major collapses are not possible with an EPBM since there is no space for the soil to flow into, *provided water inflows are controlled*. Under high water pressures, incorrect operation of an EPBM can lead to serious collapse due to blow out of material through an open screw conveyor. In stiff clays the pressure balance can help to reduce ground movements, a matter of increasing importance in existing urban environments, while the use of compressed air can be avoided. There has therefore been a steady trend in recent years to extend the use of EPBMs to most types of soft ground, by conditioning the excavated soil to suit the machine rather than limit the machine to suitable natural soils.

The application of EPBMs in sand and gravel requires mainly that the excavated soil be rendered effectively impermeable and of a plastic consistency which can be remoulded in the machine head and extruded through the screw conveyor without allowing inflow of groundwater. This may be achieved in some cases by the injection of bentonite, relatively small quantities of which provide a useful increase in plasticity. However this is not a simple operation; it is difficult to add sufficient bentonite without also adding excessive amounts of water, and the spoil produced is very messy and may cause problems in disposal. Increasingly, polymer and foam materials are preferred, and have allowed EPBM use to be extended to ever coarser and more permeable soils.

The problems of EPBMs in stiff, over-consolidated clays are less obvious. In theory such clays can be moulded to a soft plastic material by the incorporation of sufficient water to bring them to a suitably low undrained shear strength, typically between about 10 and 25 kPa. For remoulded clays this requires material at a water content corresponding to a liquidity index of about 0.4 to 0.75. Stiff clays in the ground are typically at water contents around their plastic limit. Clays of low plasticity may absorb extra water quite readily during the relatively short time that they are passing through the machine head, but it is very difficult to add exactly the right amount of water. Too little and the clay will be too stiff, and will require excessive power to remould it and to force it through the screw conveyor. Too much and the clay will rapidly turn to a slurry which cannot be passed through the machine in a controlled way.

With highly plastic clays the problem is that large quantities of water are needed to change the water content sufficiently and the clay is very impermeable. It is almost impossible to achieve a well-mixed soil of reasonably uniform consistency at the right shear strength. It may instead be possible to create a 'rubble' of chunks of the intact clay sliding in a matrix of softened soil; however in this case there is a great danger of recompacting the material into a very sticky mass which clogs up the machine head and conveyor. Similar problems can occur in clays of intermediate plasticity, though to a lesser extent.

In such stiff clays the best approach will almost certainly be to aim to create a rubble of intact clay blocks, but in a matrix of foam or polymer material which inhibits uptake of water by the clay, coats the clay blocks and enables them to slide around each other and the machine head without tending to coalesce into a mass of clay. If the matrix is also compressible, as is the case with foam, operation of the EPBM is made easier, since pressure in the head becomes less sensitive to slight differences in the rates at which material enters the head chamber and is removed from it by the conveyor.

If possible, stiff plastic clays should not have access to free water, which may enter through more permeable soil lenses or become available from slurries or early degradation of foam. The clay will start to take up water and swell, which may cause difficulties further down the handling chain.

2.5 Spoil handling

Spoil handling methods are very varied and depend on the type of tunnelling machine and other factors related to the size and length of tunnel etc. In a slurry machine the excavated material is transported from the tunnel face to the surface by the circulating slurry; the slurry has to be designed to have the correct properties at the required velocity in the pipe line to transport the excavated material without excessive power consumption or pipe and pump wear. Thixotropic properties may also be useful, so that if circulation is halted for any reason the excavated soil is held in suspension and not allowed to settle out in the pipes; however excessive stiffening may cause problems with restarting flow or clogging of pumps. Bentonite slurries may be enhanced by various additives, to control viscosity or gel strength, or slurries made from natural or artificial polymers may be considered.

The excavated material then has to be separated from the slurry, which is recirculated. The operation of the separation plant is often crucial to the success of the tunnelling process. The finer the excavated material, the more difficult it becomes to separate from the bentonite slurry carrier fluid. If the returning slurry becomes overloaded with fines its carrying capacity is reduced, pumping costs increase and at some point a decision has to be made to add fresh bentonite or renew the slurry completely. Disposal of slurry wastes may be difficult, and it is usually better to treat the material so as to make it suitable for disposal as a solid waste. Most separation plants involve a combination of processes. Simple vibrating screens will typically be used to remove particles larger than about 3-5mm. Finer material may then be allowed to settle out in settlement tanks, probably with the assistance of flocculating agents; however this is a slow process which is usually only suitable for the final stage of treatment of waste water before disposal to drains. Cyclones may be used for accelerated removal of particles down to about 0.1mm in a single stage or 0.02mm in two stages. Centrifuges may be used to remove particles down to 5 micron (fine silt) or smaller, but can only handle relatively small throughputs. They may be used to clean part of the carrying fluid (slurry) for re-use in the machine, while the remainder is re-circulated without treatment. The sludge from settlement tanks or cyclones may be further dewatered using belt presses to produce a material more suitable for tipping. Figure 5 shows a flow diagram for a typical separation plant, but considerable variations are possible depending on the size and nature of the project.

Conditioning agents in the slurry have to be chosen so as not to jeopardise the performance of the separation plant; in addition, different agents may be used to enhance the separation process. Any agents remaining in the waste for disposal should not cause it to be classified as special waste with consequently high disposal costs.

In other types of TBM the spoil is usually removed by conveyors, trucks, or some combination of these, though pumping may be possible for suitably fluid materials. Handling is generally much easier if the spoil is not too wet or fluid; the water content of wet spoil may be reduced by the addition of conditioning agents.

In an EPBM the first stage of spoil removal is via the screw conveyor from the machine head chamber. Similar comments apply here as to the machine head; the spoil must be in a suitably plastic state to form a plug and allow controlled extrusion through the screw without excessive wear or power consumption. Where the soil in the head chamber has not reached a sufficiently low permeability, the screw conveyor offers a further opportunity for injection of conditioning agents so that a 'plug' of low-permeability material is formed in the screw and prevents excessive flows of water. As the volume of soil is relatively small and is well confined, treatments at this stage may be used as 'rapid-response' control measures when ground conditions change suddenly, provided an agent with a sufficiently rapid action is available. Nevertheless it is clearly better to have advance warning of changes in ground conditions to allow suitable changes to conditioning schemes to be put in hand so that the soil is correctly treated from the cutter head onwards. Such advance warning might come from extensive site investigation, from drilling ahead of the tunnel face, or by geophysical ground-probing techniques (e.g. seismic or ground probing radar).

Once through the screw conveyor, muck may be transported by trucks or conveyor systems, and similar comments apply as for open face TBMs.

Many of the points discussed above in sections 2.4 and 2.5 in relation to EPBM tunnelling shields could equally apply to auger-type microtunnelling systems. Use of conditioning agents could allow such systems to be used under ground and groundwater conditions for which they would not otherwise be suitable.

2.6 Spoil disposal

Disposal of excavated material is an ever more important aspect of any major tunnelling activity. Spoil in good condition may have a positive value for fill elsewhere on the project or at locations nearby, if only for landscaping. Spoil which is very wet or contaminated may on the other hand occur high disposal costs, both in its transport and in disposal charges. Any conditioning of the spoil which leads to problems of disposal is unlikely to reduce the overall costs of the project. Steiner (1995) compares the difference in end-product from alternative separating processes following slurry shield excavation of glacial soils with a wide range of particle sizes. Centrifuge separation was found to be much more effective than bandfilter (belt) pressing in removing the fines (including bentonite contamination), and produced spoil which was much easier to dispose of. However performance of the bandfilter might have been improved by the use of coagulating agents.

Potential chemical and biological effects on the environment in both short and long term have to be taken into account. These effects are considered further in Section 6 below.

2.7 Lubrication of the pipe line during pipe jacking

A separate, but possibly inter-related, application of materials used for soil conditioning in the tunnelling process is as a lubricating agent between pipes and ground during pipe jacking and microtunnelling. The exact requirements of such an agent vary significantly with the ground conditions. In unstable ground, particularly sands and gravels below the water table, the primary function of the agent is to provide a fluid pressure to support the excavated tunnel bore and prevent collapse of the ground onto the pipes. To do this in permeable ground requires the formation of a filter cake at the soil interface, in the same way as at the tunnel face in a slurry shield machine. Bentonite slurries, perhaps with polymer additives, are usually suitable for this purpose.

Provided the ground is stable, a tunnel cut to a slightly greater diameter than the outer diameter of the pipes will minimise contact between pipes and ground. Pipes will normally then slide along the base of the tunnel bore, generating frictional resistance in proportion to their weight. If the overcut is filled with a fluid lubricant, the pipes will become partially or completely buoyant, so that the contact forces between pipes and ground will be greatly reduced. The lubricant must also obviously have a small shear strength of its own, and this may become the main resistance to forward sliding of the pipes. Pipes at neutral buoyancy in a slurry lubricant of low shear strength may experience almost negligible resistance, and very long pipe jack drives become practical with modest jacking forces. Drives of several hundred metres are now commonplace, and drives of over 1000m have been achieved on several projects. The effectiveness of slurry lubrication has been demonstrated and explained by research projects in the UK and France, see for instance Milligan and Marshall (1998) and Pellet and Kastner (1998).

Where full lubrication of this kind is not required, the use of lubricating agents in sandy soils or clays of low plasticity may allow the pipe to slide on a layer of mixed soil and lubricant with a significantly reduced coefficient of friction.

In stiff plastic clays the use of water-based lubricants may be counter-productive. Water from the lubricant can gradually penetrate the soil, allowing it to expand and close onto the pipe. The resulting 'squeezing' stresses between pipe and ground may be quite large, and generate high resistance to jacking even when the coefficient of interface friction is small. The use of inhibiting agents in a slurry may prevent the absorption of water by the soil, or lubricants may be used which do not interact with the soil. The alternative approach of creating a relatively large overcut, so that even after swelling the clay does not close on to the pipe, has the sometimes serious disadvantage of allowing greater ground movements to occur.

3. BASIC CONCEPTS: MATERIALS, PROPERTIES AND TESTS

3.1 Introduction

Consideration of the properties of and requirements for ground conditioning and lubricating agents depends on a number of basic concepts relating to: the physical and chemical natures of the materials; their existence as solid, liquid and gaseous phases and any combination of these; and their physical and chemical interaction with water and soils of different types. In addition, they must be non-toxic, easy and safe to handle, and biodegradable. For practical methods of introducing the materials into the soil, they are normally used in liquid form, often as slurries which may have thixotropic properties, in which case viscosity and gel strength are important. Alternatively they may be used as foams, raising questions of stability and compressibility.

3.2 Surface effects, dispersion, flocculation and gelling

Mineral particles in a slurry generally carry electrical charges, the nature and intensity of which vary with the particle surface characteristics and the chemistry of the liquid phase. Polar water molecules may then be adsorbed onto the particle surface, forming a layer of 'bound' water surrounding each particle. The result of the two effects is to produce repulsive forces between particles, which are greater than attractive Van der Waal's forces except when the particles are very close together (Figure 6). The particles in a slurry therefore tend to keep apart from each other in a 'dispersed' condition (Figure 7a). The effects are most noticeable with small particles (clay/silt rather than sand/gravel) since the relative surface areas are much larger, and gravitational forces are much smaller. Under some conditions the plate-like particles of clay minerals may have different charges on the edges and faces of the particles, and are able to clump together in a 'flocculated' structure (Figure 6b). The large flocs settle out of the slurry much more readily than the small individual particles. In some circumstances it is required to cause settlement of particles, in which case flocculating agents are used to overcome the dispersive effects, while in other cases a dispersed condition is required and dispersants may be used to inhibit flocculation.

Some slurries demonstrate the effect known as thixotropy, whereby they 'set' to a gel-type material if left undisturbed, but revert to a viscous fluid when sheared. The alternation between fluid and gel may take place any number of times. The phenomenon is well known in 'non-drip' paints. A gelled structure is illustrated in Figure 7c; gels of thin clay particles may contain only a few percent of solid material.

3.3 Rheology

Rheology is the study of the flow properties of materials. As the use of soil conditioning and lubricating agents is greatly affected by the flow properties of the materials and their mixtures with soil, some of the basic terms and concepts are introduced here.

Viscosity is the relation between shear stress and shear strain rate in a liquid. Thus if two planes in a liquid are separated by a distance D and are moving parallel to each other at a relative velocity V (see Figure 8), the shear stress τ in the liquid between the plates is given by $\tau = \mu V/D$, where μ is the coefficient of viscosity. Units of viscosity are $N.s/m^2$ or Pa.s, but are normally expressed in terms of *centipoise* (1/100th of a *Poise,* named after a French scientist); 1.0 cp is equal to 10^{-3} $N.s/m^2$. The viscosity of water at 20^0C is 10^{-3} $N.s/m^2$.

Newtonian fluids are those for which the viscosity is independent of the rate of shear, and include water and oil; the shear stress increases linearly with rate of shear. Non-Newtonian behaviour may be described by models such as Bingham plastic, pseudoplastic or dilatant (Figure 9). The first shows an initial yield stress below which no shear occurs, then a linear increase of shear stress with strain rate (the plastic viscosity). Pseudoplastic or dilatant behaviour may be represented by a power law curve, so that it appears as a straight line on a logarithmic scale of shear rate:-

$$t = K.(V / D)^n$$

where K and n are constants with

$n < 1$ for a pseudoplastic fluid

$n > 1$ for a dilatant fluid and

$n = 1$ for a Newtonian fluid

Viscosity is affected by temperature, most liquids becoming less viscous at higher temperatures. In some slurries the viscosity decreases at high shear rates, and this is referred to as 'shear thinning'. Time effects also occur in many fluids; thixotropy is the most important example. Many slurries used in tunnelling are quite complex in their rheology, but may be treated for practical purposes as Bingham fluids with thixotropic properties.

Viscosity may be measured by a number of different types of apparatus, known as viscometers. Assuming the fluid to act as a Bingham plastic fluid, a minimum of two readings at different shear rates are needed to define the yield point and the plastic viscosity. A simple device often used on site is the Marsh cone; in this the time taken for a given volume of the fluid (1000cc or 1.0 US quart) to flow out of a standard conical funnel provides a measure of the viscosity. An approximate relationship between the Marsh funnel reading and the viscosity measured by a viscometer is given for bentonite slurries in Figure 10. Other tests which are used to categorise slurries in the field are for the density, using a 'mud balance', and sand content. Details of tests are given by Jefferis (1992) and in Appendix A.

3.4 Bentonite slurries

The name bentonite is popularly used for a range of natural clay minerals, principally potassium, calcium and sodium montmorillonites. The term 'smectite' is also used for the group of minerals which includes montmorillonites. Because of the chemistry and microstructure of the clay particles, they have a strong ability to absorb water and are able to hold up to ten times their dry volume by absorbtion of water. Montmorillonite consists of very thin flat crystalline sheets of clay minerals which are negatively charged and are held together in 'stacks' by positively charged sodium or calcium ions in a layer of adsorbed water (Figure 11). In particular the particles of sodium montmorillonite are extremely small and thin, being typically of the order of 1.0µm or less in length and 0.001µm thick. The ability to absorb water comes from the relatively low bonding energy of the sheets, which allows water molecules to be adsorbed onto the internal and external sheet surfaces. Calcium ions provide a stronger bond than sodium, so that calcium montmorillonite swells less readily than sodium montmorillonite. Potassium ions provide much stronger bonding between clay sheets as the potassium ion is of exactly the right diameter to fit into the clay structure with negligible gap between the clay sheets. A similar material to montmorillonite but with potassium bonding is the non-swelling clay mineral known as illite (Figure 11). The substitution of sodium by calcium or potassium ions in montmorillonite greatly reduces the ability of the clay structure to hold water.

A useful index distinguishing between different clay mineral types in the field is the *activity*, defined as the ratio of the plasticity index to the clay content, both measured in percentage. For kaolinitic clays the activity is about 0.5, for illite 0.5 to 1.0, while for smectite it may range from 1 up to 7. London Clay, mainly a mixture of illite and smectite, has an activity of about 0.95.

The best grades of bentonite are primarily sodium montmorillonite (preferably over 90%), while the calcium form gives lower grade material. Much commercial sodium bentonite, including that produced in the UK, is created by ion exchange from calcium bentonite, but the most freely dispersing type is generally reckoned to be the naturally occurring Wyoming sodium bentonite. This provides slurries with very good viscosity, but relatively low gel strength. UK bentonites tend to be less dispersive, give lower viscosities for the same slurry density, but higher gel strengths. Bentonites vary widely in quality around the world, and these variations must be taken account of in the design and specification of slurries. Properties of bentonite slurries are often enhanced by the addition of small quantities of polymers (see below).

Bentonite slurries are made by adding bentonite to fresh water and mixing in a high-shear mixer (to ensure proper dispersal of the clay particles), and then leaving the slurry for a recommended time to ensure sufficient hydration of the clay. Slurries are usually formed from a few percent of bentonite in water. Bentonite slurries are thixotropic and typically form a gel at concentrations above about 5% by weight in water. For a more detailed discussion of the nature and properties of bentonite slurries see Jefferis (1992).

3.5 Polymers

Polymers are essentially large, long-chain molecules formed by the linking together of large numbers of small chemical ‘building blocks’ or monomers. Homopolymers are achieved by polymerisation of a single basic monomer unit, copolymers by two or more different monomers. A polymer material may exist in many different forms, depending on the lengths of the polymer chains (measured by the molecular weight), the presence and nature of any linking between polymer chains, and the existence or not of structured (crystalline) groups of molecules. Polymers exist widely in nature, and natural polymers which may be used in tunnelling include starches, sugars, celluloses, and proteins. Some of the man-made polymers which have found applications in tunnelling are polyacrylamides and polyacrylates, partially hydrolysed polyacrylamides (PHPA), carboxymethyl cellulose (CMC), and polyanionic cellulose (PAC).

One of the most important groups of polymers used for soil conditioning and lubrication are the polyacrylamides (PA) and their derivatives, which have been extensively developed for the mineral processing industry, where they have largely replaced natural products such as starch. Lambe (1953) discussed the conditioning of soil for strength and compactability using sodium polyacrylate more than 45 years ago. High molecular weight ($>10x10^6$) water-soluble polyacrylamides have been used for many years to aid separation of solids from liquids by acting as flocculants. Polyacrylamides of lower molecular weight (<300,000) may be used as dispersants, while cross-linked versions produce water-absorbent polymers. A wide range of polyacrylamides is possible, with molecular weights ranging from several thousand to over 10 million, and with ionic character from 100% cationic to 100% anionic (monomer units having positive or negative charges respectively). They retain their water solubility due to their high degree of linearity; the introduction of high degrees of cross-linking produces materials which do not dissolve but swell and absorb large quantities of water. Typical basic monomers and their polymerisation to form PA polymers are shown in Figure 12a. Linear co-polymerisation of acrylamide and sodium acrylate to form an anionic PA and cross-linking by a methylene bridge are shown in Figures 12b and 12c.

Flocculation is thought to occur mainly by bridging, whereby the polymer molecules attach themselves to the surface of the mineral particles, leaving projecting loops of varying length. As particles collide these loops entangle with each other and lock the particles together (Figure 13).

In addition to the synthetic PA-based polymers, a number of natural products have been used as flocculating agents. The majority are polysaccharides such as starches and guars; starches have been most widely used, notably for the flocculation of bauxite in the alumina industry.

PA polymers of low molecular weight act as dispersants by increasing the overall negative surface charge on solid particles to which they become attached, reducing the natural tendency of particles to flocculate as a result of the variable distribution of charge on particles, and hence maintaining a dispersed structure of lower viscosity.

Water-absorbing polymers are PAs of very high molecular weight ($>10^7$) and a high level of cross-linking. As a result, they cease to be soluble in water, despite the presence of polar amide and acrylate groups, but merely absorb water and swell. Water-absorbing capacities of 500-600 times the weight of the polymer are possible with pure water, but 100 times is more realistic for water containing dissolved solids.

Slurries formed from polymers are not strictly speaking thixotropic, but exhibit stiffening due to meshing of the long molecular chains. They have been extensively developed by the drilling industry as high-performance alternatives to bentonite slurries. They have applications as drilling fluids and pipe lubricants in ground conditions (high-plasticity clays and shales) where bentonite slurries may cause swelling of active clay minerals and consequent jamming of the pipe or drill string. However their relatively high cost has meant that they are not usually economically viable in civil engineering applications. Instead, polymers generally find use as additives to enhance the performance of bentonite or clay slurries or pastes. They may act to improve the ability to form a filter cake, increase lubricity, or maintain a dispersed structure. Alternatively, polymers on their own or in foam formulations may be introduced in relatively small proportions to lubricate and plastify coarser soils.

Polymers are available in a variety of forms, but most commonly either as solid beads or dissolved or dispersed in water or oils. Dry polymer beads may be difficult to dissolve quickly as they tend to lump and form a gel layer on the outside which inhibits the further ingress of water. It helps to provide agitation, but high shear mixers should not be used as they tend to break up the large molecules.

Generally, for maximum effectiveness both bentonite and polymers should be used in water with pH in the range 8.5 to 9.5. However pH higher than 9.5 has the benefit of acting as a biocide, preventing biological breakdown of polymers. If necessary, soda ash should be added to the water to raise its pH. The bentonite should be added next, and the slurry properly mixed in a high-shear mixer and allowed to hydrate, then finally the polymer.

3.6 Foams

Foam is essentially a gas, usually air, dispersed as bubbles in a liquid. It is created by using a surfactant to reduce the surface tension at the air-water interface (for details of the theory and properties of surfactants see Porter (1994)). The bubbles have an internal pressure in excess of atmospheric pressure which is related to the size of the bubbles and the strength of the bubble membrane. The bubbles in a 'dry' foam, in which the wall thickness of the bubbles is small compared with the size of the bubbles, are not spherical but join together to form polyhedra which are almost regular dodecahedra (having 12 faces), with nearly planar liquid films between the bubbles. A two-dimensional section is shown in Figure 14. The thin films have surface energy, and the action of the surfactant is to reduce the surface energy and hence the amount of energy required to produce the foam. For a given air/liquid ratio, the surface area and hence total energy increases as the average bubble size reduces.

There are two basic types of foaming agent - synthetic detergents and ones that are protein based. Typical constituents of protein foams are 20-40% protein foaming agent and 3-10% glycol-based foam booster. Typical constituents of synthetic foams are 5-30% synthetic detergent and 15-20% glycol ether foam booster. Both types may have fluorocarbon performance enhancer (<5%) and soluble polymer (<5%). They may also have various additives: preservatives, to prevent mould growth; metal salts in protein foams; anti-freeze agents; corrosion inhibitors; solvents, to reduce viscosity; substances to stabilise the foam bubbles; and dyes for brand recognition. Synthetic foams are composed of a mixture of anionic hydrocarbons, solvents and stabilisers. They tend to have low stability because of their relatively rapid drain times; the liquid drains from the bubble walls until they have insufficient strength and collapse. Protein foam agents consist of hydrolysed protein, solvent, sodium chloride, salts of iron and calcium and preservatives in an aqueous solution. The starting material for the protein may be soya beans, corn gluten, animal blood, horn and hoof meal, waste fish products or feather meal. Protein foams are generally stiff, stable and have low drainage rates. Polymers may be added to foaming agents to increase the viscosity of a foam and improve its thixotropic properties. The effects of such additions tend to be more reliable with synthetic foams, for which a wide range of additives is available. Protein-based foamers are harder to modify, as the electrical charges created are unknown (Lyon, 1999b).

The properties of a foam are related to the expansion ratio (the ratio of the foam volume to the original liquid volume), and also to the nature and concentration of the foaming agent in the liquid. In a typical application, the expansion ratio might be 10 to 20, so that 1000 litres of foam would contain 100 to 50 litres of liquid, the rest being air. The liquid in turn would typically contain 1 to 3% of concentrate, the remainder being water. Thus even if large quantities of foam are required, and the concentrated agent is expensive, the cost of the foam may be quite modest. Similarly, the increase in volume of both solid material and water in the excavated spoil is much less than when a clay slurry additive is used.

All foams are metastable, and will eventually collapse, but foams can be made which are 'stable' for long periods. For use in an EPBM it is important to know the total period for which a foam would be stable in the foam-soil mixture in the working chamber and screw conveyor. Beyond this period the foam may collapse during an unplanned delay in tunnelling, causing loss of face pressure, loss of workability in the material to be excavated and possibly catastrophic loss of the earth pressure balance plug. Foam stability is a function of the size and uniformity of the bubbles and of the strength of the bubble wall. Bubble size should be as small and uniform as possible; in foams with varying bubble sizes the larger bubbles tend to 'capture' the smaller bubbles leading to rapid collapse of the foam.

Some standardised tests have been developed for foams because they have been used for various purposes (e.g. for fire-fighting, foamed concrete) for quite a long time. The density of a foam is a function of its expansion ratio and its stability is measured by its drainage time. Details of a standard test to measure the foam expansion ratio and drainage time (25%) are given in Appendix A. Some research workers have used a half-life test, in which the time taken for a volume of foam to lose half the initial liquid volume is measured (Decon 1996, Quebaud et al.1998). Half-lives up to several hours are achievable with suitable foams.

Foam compressibility can be measured by varying the air pressure applied to a volume of foam contained in a transparent cylinder. Since foam is largely air, its compressibility might be expected to conform to the gas law pV = constant; expressing this relation in terms of the expansion ratio K (total volume of foam divided by original volume of liquid), the volume at absolute pressure p is related to that at atmospheric pressure p_a by

$$K = \frac{p_a}{p}(K_a - 1) + 1$$

where K_a is the expansion ratio at atmospheric pressure. Typical results are shown in Figure 15. They match quite well with the theoretical behaviour, and the behaviour is fully reversible, the slight stiffening in the response being due to drainage of the foam being accelerated by the effects of pressure.

The rheological properties of foams exhibit similar variations to those of slurries. Behaviour may be described by similar models (Newtonian, pseudoplastic, shear thinning etc), but reproducible values are more difficult to obtain as the behaviour may be significantly affected by the test procedure. Dry foams will generally exhibit non-Newtonian behaviour with a yield stress.

4. MATERIALS AND APPLICATIONS

4.1 Bentonite

The principal use of bentonite in tunnelling is in slurries in slurry shields and as a ground support and lubricating medium around jacked pipes. Such slurries generally have only about 3% by weight of bentonite, giving a Marsh cone reading of 30-40 seconds. The first requirement of the slurry is that it should form a 'filter cake' of consolidated and gelled bentonite against and within the soil, which then becomes a low permeability membrane able to transmit fluid pressure in excess of groundwater pressure into effective stress between soil particles and hence stabilise the ground (Figure 16). To do this it must not be able to penetrate too readily into the ground; in open soils a slurry may simply dissipate into the ground without transmitting any significant stresses into the soil, causing large consumption of bentonite and poor ground support. Jancsecz and Steiner (1994) studied the penetration of slurry and produced the formula

$$s = \frac{\Delta p.d_{10}}{3.5\boldsymbol{t}_s}$$

where s is the penetration distance, d_{10} is the particle size such that 10% by weight of the soil is of smaller particle size, ϑ_s is the shear resistance of the slurry, and)p is the difference between the slurry pressure p and the ground water pressure u. For clean slurries and typical values of)p, penetrations of several metres result in soils any coarser than medium sand with typical shear strengths of the slurry of 20 to 50Pa, and will be unacceptable when d_{10} exceeds 2 to 3mm. However if the slurry contains soil fines (silt and fine sand) which help to block the pores, penetration is greatly reduced and there has been satisfactory experience in both the UK and Japan of using slurry support in much coarser soils.

Jefferis (1992) provides an expression which includes the porosity of the soil n:

$$s = \frac{\Delta p.d_{10}}{\boldsymbol{t}_s}.\frac{n}{(1-n)}.f$$

where f is a factor to take account of the geometry and tortuosity of the flow paths within the soil, and may be about 0.3. For typical values of porosity this gives considerably shorter penetration lengths than does Jancsecz and Steiner's expression.

Anagnostou and Kovari (1996) quote a similar expression from the German Standard DIN-4126 (1986):

$$s = \frac{\Delta p.d_{10}}{2.0\boldsymbol{t}_s}$$

They use this to determine slurry penetration into soils of different grain size, and hence the pressure gradients within the ground in front of the shield and the resulting factor of safety against face collapse. They then investigate the inter-related effects of grain size, soil permeability, slurry pressure, slurry shear strength, rate of slurry penetration and tunnelling advance rates. They conclude that slurries with 7% bentonite content may be used to extend effective support for coarser soils with d_{10} grain sizes of up to 6mm, but problems with face instability are likely to occur for practical tunnelling rates once the soil permeability exceeds about 10^{-4} m/sec. In practice slurries with such high bentonite concentrations are difficult to work with, and it is much more effective to use thinner slurries containing silt and fine sand to act as pore-blocking material .

To reduce penetration and improve cake formation, polymers may be added. Their long-chain molecules act as reinforcing fibres and form a 'net' to retain the bentonite particles, bridging the soil pores. Sodium CMC polymers have been extensively used in Japan for this purpose, for which PAC materials are also suitable. They may act well in combination with silt and fine sand from the previously excavated soil which has been retained in the slurry and will block pores between larger particles. Steiner (1996) was able to investigate the penetration of different density slurries into a well-graded glacial gravel with a small fines content and 10-20% in the sand range. Slurry with a density of 1.03 to 1.05 Mg/m^3 penetrated 6 to 8m. Increasing the slurry density to 1.08 to 1.12, with $50kg/m^3$ bentonite, and adding $1kg/m^3$ of polymer and retaining some sand, reduced the penetration to 4 to 6m. Slurry with a density of 1.14 to 1.24 penetrated 0 to 2m. The pressure differential is not given.

If lubrication of the pipe line is required when pipe jacking in clay, an inhibited bentonite slurry may be needed. As discussed above, plastic clays which come into contact with aqueous slurries will absorb water and swell. The ground may swell sufficiently to close the overbreak and increase the contact stresses between pipe and ground and hence the jacking resistance. There are two methods of protecting clays in this instance: changing the reactivity of the clay (see section 4.4); and providing a barrier between water and clay particles. The latter is achieved using one of the highly anionic polymers specially produced for this purpose, such as PHPA, which act by binding the surface layer of water to the clay surface and preventing any further ingress of water to the clay particles. Only small dosages are needed, typically of the order of 0.05 to 0.1%.

The other use of bentonite is as an additive to the head chamber of EPB shields to confer or increase the plasticity and reduce the permeability of coarse-grained soils. The required quantity of bentonite to be added is given by Kusakabe et al. (1999) (from the Japanese Association of Earth Pressure Balance Shield with Additive Method) as:

$$D = a.(30 - p_{0.074}).a + (40 - p_{0.25}).b + (60 - p_{2.0}).g$$

where *D* is the concentration given by:-

$$\frac{\textit{Weight of additive}}{\textit{Weight of water}} \times 100\%$$

and $p_{0.074}$ = percentage of soil passing 0.074mm
$p_{0.25}$ = percentage of soil passing 0.25mm
$p_{2.0}$ = percentage of soil passing 2.0mm
$\alpha = 2.0$
$\beta = 0.5$
$\gamma = 0.2$

The expressions in parentheses () all have minimum values of zero, and *a* is a coefficient depending on the uniformity coefficient of the soil (*Uc*):-

$a = 1.0$ for $Uc>4$
$a = 1.1$ for $4>Uc>3$
$a = 1.2$ for $3>Uc>1$

4.2 Foams

The principal use of foam in tunnelling is as a soil conditioning agent in EPB machines: it may also have applications in both slurry-type and auger-type microtunnelling systems.

Foam is produced in a tunnelling machine by a compressed air system. Foam solution and compressed air are fed at the same pressure (typically around 8 bar) to a junction piece or mixing chamber, and then out through a diffuser unit, conditioner or lance which converts the fairly coarse foam produced in the mixing chamber to a micro-cellular foam. Ideally most of the foam air pores should be less than 1mm in diameter (Cash and Vine-Lott 1996). The delivery system should be mounted as close as possible to the outlet position as foam is rapidly degraded if pumped a long distance through narrow pipes. For multiple injection ports, each port should have its own delivery system, and these should be able to operate at up to 16 bar as an aid to clearing blockages.

The amount of foam to be provided is usually expressed as a foam mixing ratio, *Q*, which is the volume of foam divided by the volume of excavated soil (in %). Based on experience accumulated over ten years, Kusakabe et al (1999) give the required foam mixing ratio (from the Japanese Foam Shield Method Association) for coarser soils as:

$$Q = \frac{a}{2}[(60 - 4.0X^{0.8}) + (80 - 3.3Y^{0.8}) + (90 - 2.7Z^{0.8})]$$

where *X* is the percentage of soil passing 0.074mm
Y is the percentage of soil passing 0.25mm
Z is the percentage of soil passing 2.0mm
and the expressions in parentheses ( ) all have minimum values of zero.

The coefficient *a* depends on the uniformity coefficient of the soil (*Uc*):-
$a = 1.0$ for $Uc>15$
$a = 1.2$ for $15>Uc>4$
$a = 1.6$ for $4>Uc$

Bezuijen at al. (1999) provide an alternative concept, which gives rather different required foam volumes, whereby the quantity of foam mixed with the soil must produce a porosity of the soil greater than the maximum porosity of the soil alone at the pressures obtaining in the head chamber. As the pressure drops through the screw conveyor, the porosity will increase further as the air bubbles in the foam expand. The vane shear strength of a sand-water-foam mixture was measured at less than 2 kPa. Importantly, these authors also reported that a sand-water-foam mixture mixed under pressure was stable for much longer periods of time than the foam on its own.

The volume of foam required for stiff clays is not yet well defined, but appears from limited evidence to be around 30%. Cash and Vine-Lott (1996) suggest that the foam flow rate should approximately equal the void content of the cut material after allowing for pressure effects. For example, a cutterhead excavating 1m^3/min which bulks up by 20% after excavation will need 200 litre/min of foam at the face pressure. Thus if the absolute face pressure is 2 bar, the volume at atmospheric pressure is about 400 litre/min.

4.3 Polymers

The use of polymers for tunnelling seems to have originated in the USA but been developed mainly in Japan, where CMC polymers were widely used as agents to increase the viscosity of bentonite slurries and improve cake-forming, and hence enhance face support. Other polymers used for the same purpose are polyanionic cellulose and polyacrylamides; they also increase lubricity and can inhibit clay swelling. The performance of the bentonite slurry may be greatly enhanced; however, although only small quantities of polymer additive are required, typically 0.5% or less, the increase in cost is significant since the cost of polymer may be ten times that of bentonite. PA dispersants may also be added to bentonite or other clay slurries to maintain a dispersed structure in the slurry, prevent flocculation and settling out of solids, and keep viscosity low for efficient pumping of the slurry. ‘High-solids’ slurries are then possible which can maintain face stability even in very coarse-grained soils.

Polymers may be added to the face chamber of EPB shields to plastify the excavated soil, either on their own or as an additive to foam. When they are used without foam, the water content of the excavated ground is important in determining the properties of the plastified material. Water absorbent polyacrylamide polymers may also be added at this stage or in the EPBM screw conveyor to help control water flowing into the machine and make the final spoil easier to handle. The use of soil conditioning agents in EPB shields is discussed further in Section 4.5.

Very high molecular weight PAs find a use in flocculating slurries to remove solids in belt presses in separating plants for slurry tunnelling. The flocculant is added just before the press so that large flocs are formed to allow rapid dewatering in the first stage of the press; the flocs then collapse under higher pressure in the later stages, allowing perhaps 80% of the remaining water to be squeezed out. For the relatively high pH conditions in typical tunnelling slurries, anionic PAs are more effective, though improved performance may be achieved by a second stage treatment with cationic flocculant following an anionic first stage. The performance of the separating plant must be considered when polymers are to be used in the main slurry, as polymers of very high molecular weight may tend to block screens in the early stages of separation.

Water-absorbing polymers, such as cross-linked PAs, may be added to wet excavated material to render it dry enough for normal handling to tip. The same effect may be achieved more cheaply with lime or cement, depending on the conditions controlling disposal.

4.4 Other materials

One approach to reduction in the swelling potential of clay soils involves converting the clay type to one which is less ready and able to absorb water, usually by exchanging specific ions within the clay minerals. Swelling clays contain a relatively high proportion of montmorillonite, while less active clays are mainly illite and kaolinite clay minerals. For reasons discussed in Section 3.4, the addition of potassium chloride is especially effective in reducing the swelling potential.

Various additives may be used as dispersants and thinners of bentonite slurries, including lignosulphonates and complex phosphates. Various types of oil may be used to increase the lubricity of slurries; for environmental reasons these should be natural biodegradable oils, such as jute or palm oil

4.5 Summary of lubrication and soil conditioning in EPB shields

Potential uses and likely dosage rates for lubricating and soil conditioning agents in an EPB shield, based on suggestions by Morrison (1997), are summarised in Table 3. Generally higher dosage rates of additives are needed as ground conditions move away from those that are ideal for EPBM operation, towards both stiff, highly plastic clays and coarse granular soils. Conditions in the latter become particularly onerous if there are high groundwater pressures. For mixed faces it may be necessary to employ suitable conditioning for both types of soil, unless they can be broken up and mixed to a reasonably homogeneous material within the head chamber. It is clear from practical experience (see Section 7) that correct design of the shield to allow lubricating and soil conditioning agents to work satisfactorily is absolutely critical. Some important points to note are:-

a. Additives should be injected as early as possible in the process, preferably at the point of cut or excavation
b. In stiff clays or soft rocks, the ground must be broken up by the tunnelling tools into pieces of suitable size to be carried by the additive (foam).
c. In soils containing cobbles and boulders, grizzly bars must be fitted to the shield apertures so that particles too large to be handled by the system behind the cutter disc are broken up before entering the

chamber. This sizing is critical, and may determine the type of screw, an open centre screw being able to handle larger particles than a screw with a central shaft.

d. Sufficient ports must be provided to enable the conditioning agents to mix as quickly as possible to provide a uniform distribution within the excavated soil. Particularly important points are at the centre of the cutter head where conditions are poor for mixing and at the outer rim of the cutter head where the volume of soil swept by each revolution of the head is greatest.

e. Design of the interior of the chamber should be such as to provide the best possible mixing of soil and additives in the time available, and avoid locations where untreated soil can collect, coalesce, and in time block the system.

f. Each port for injection of soil conditioning agent should have its own delivery line, so that if the port becomes blocked it is possible to blow it clear (by connecting to a high pressure hydraulic line); if a single line serves several ports and one becomes blocked, additive will simply be diverted to other ports and it is impossible to clear the blocked one. This is particularly critical with reference to face ports; these are the most likely to become blocked, while each additive stream must pass through a hydraulic slip ring to reach the face. Design of the port itself is also important in minimising blockage and assisting in good mixing with the soil.

Factors which are critical to efficient mixing of spoil and conditioner include the position and number of injection points, the rotation speed of the cutter head, the shape of the excavation chamber and lead-in to the discharge point, the mixing time in the cutting head, the method of injection and control of the injection rate. Regular sampling and monitoring are necessary to establish the effectiveness of the process and minimise costs.

5. TEST METHODS FOR CONDITIONED SOIL

Various tests have been devised to assess the performance of foam-soil mixtures, to try to investigate the mixtures under conditions representative of those pertaining in the EPBM. These tests have been of a research nature and none has yet been standardised. However some sort of consensus seems to be appearing in the range of tests which may be useful, with similar avenues being explored in Germany, France and the UK (and probably elsewhere).

Some of the tests that have been devised are:-

i. *Foam penetration*. The purpose of this test is to determine how far ahead of the cutter head foam injected at the face may penetrate into the ground. If the penetration is too great the consumption of foam may become excessive, the foam may not be stiff enough to prevent outflow of groundwater, and the pressure gradient at the face may be insufficient to maintain an adequate support pressure; if penetration is too little, the foam may again be unable to prevent flow of groundwater. The apparatus used is shown schematically in Figure 17; foam is forced under pressure to penetrate the soil sample in the base of the test cylinder against a back-pressure in the pore water representing the groundwater pressure, and the rate of penetration measured (Quebaud et al. 1998, Maidl 1995). Results of a test reported by Quebaud et al.(1998) are shown in Figure 18; initial penetration to a depth of about 30mm is almost instantaneous. However it is clear that the mechanics of penetration at the face of a tunnelling shield through localised ports in a moving cutter wheel are very different from those pertaining in this test. Bezuijen et al. (1999) reported that no penetration of foam was observed from a sand-water-foam mixture into sand, as opposed to the penetration of pure foam into sand.

ii. *Mixing test*. Tests have been devised using a pan mixer similar to a small concrete mixer, a pug mill or large food mixer (Quebaud et al. 1998, Decon 1996, CONDAT). The soil is stirred around in the pan by a system of blades and the power consumption measured. Foam (or other conditioning agent) may then be introduced and measurements made of the time for mixing to take place and of any change in power requirements for different quantities of additive. Reductions in power consumption of over 50% for a sand/foam mixture have been reported, as shown in Figure 19 (Quebaud et al. 1998). Tests of this kind are obviously intended to model conditions within the EPBM head chamber; ideally it ought to be possible to apply a confining pressure in these tests to represent the earth balance pressure in the chamber. Bezuijen et al. (1999) report on tests in which a chamber is pressurised to 350 kPa and foam then injected into sand through a rotor which steadily penetrates the sand, representing the cutting wheel of a tunnelling machine. The apparatus is shown on the left in Figure 20. The removal of the conditioned sand through a screw conveyor is then studied using the apparatus shown on the right in Figure 20; results of the latter tests have not yet been reported.

iii. *Slump test*. Simple slump tests as performed on fresh concrete have been used to provide a measure of the plasticity of the soil (Quebaud et al. 1998, Maidl (1995), CONDAT). Slump tests have the advantage of having been standardised in many countries. Quebaud et al. suggest that a slump of 12cm is required to provide a mixture with the optimum characteristics for plastic flow in an EPBM. Other tests taken from geotechnical engineering might also be considered for this purpose, such as cone penetration tests. It may be possible to determine correlations between the results of mixing tests, slump tests and performance in the field so that either or both of the former may be used to predict the field performance of different materials or dosing rates.

iv. *Permeability test.* The permeability of a conditioned soil may be measured in a constant-head permeameter as normally used for measurements on soils. It has been suggested that the coefficient of permeability of the soil k must be below 10^{-5} m/s for adequate control of water flow through an EPBM to be maintained. As a result of conditioning, substantial reductions in permeability, by over two orders of magnitude, were reported by Quebaud et al. (1998). Bezuijen et al. (1999) reported that the final permeability of the sand-water-foam mixture depends critically on the degree to which pore water is replaced by foam. Replacement increases as the applied pressure gradient increases, but under practical conditions in the field full replacement is not possible. When 83% replacement was achieved, the permeability of a fine sand decreased from $5x10^{-4}$ m/s to $2.5x10^{-6}$ m/s; at 50% replacement the permeability dropped to $1.5x10^{-5}$ m/s, but with no replacement the permeability only dropped to $1.5x10^{-4}$ m/s.

v. *Compressibility.* Some compressibility of the foam-soil mixture in an EPBM head chamber is very beneficial; it allows some differences to occur between the rate of excavation at the face and of muck removal through the screw conveyor without excessive variations in pressure and hence either possible loss of effective face support or overloading of the machine. The compressibility may be measured in a transparent cylinder similar to that used in the foam penetration test ((i) above). It is possible that measurements of both compressibility and permeability could be conveniently made under different ambient pressure conditions in a Rowe cell.

vi. *Adhesion/friction test.* The purpose of this test is to measure the adhesion and/or friction between the foamed soil and a metal surface, to give an indication of the possible reduction in wear and power consumption due to lubrication of the interface. Quebaud et al. (1998) describe a simple test to measure a friction angle of the mixture on a sloping stainless steel plate. A more realistic test might be developed using a shear box or ring shear apparatus whereby continued sliding over an interface under realistic confining pressures could be achieved. A shear test (without the interface) might also be a simpler test to investigate the same effects as in the mixing test described above.

6. ENVIRONMENTAL ASPECTS

Information regarding the environmental effects of soil conditioning agents is at present rather limited and difficult to compare on a product-by-product basis, there not yet being a generally-accepted suite of tests to be undertaken for any particular application. Additives used in bentonite slurries in slurry machines may largely be retained within a closed system (until the end of a project) and it is usually economic to recover as much as possible from the spoil before dumping. However additives used to assist separation in the separation plant will usually remain in the muck to be disposed of, while slurry used to lubricate a pipe jack will remain in the ground after completion of the drive. Conditioning agents added in EPB shields will usually remain in the excavated material. Environmental aspects may therefore be very important in determining the costs of disposal, for instance in whether the spoil may be used for engineering or landscaping purposes or would have to be treated as contaminated waste. In addition, tunnelling operatives may have to work in close proximity to soil containing additives, raising questions of toxicity and danger to health. Conditioning agents should therefore generally be non-toxic and biodegradable. However over-rapid biodegradation may itself cause problems, for instance if run-off enters water courses and the degradation reactions de-oxygenate the water. Care therefore may need to be taken with run-off from newly deposited spoil.

Although non-toxic, synthetic PA-based polymers degrade very slowly and therefore remain present in the excavated material. The semi-synthetic materials such as CMC or PAC degrade rather more rapidly and are non-toxic. More recently, natural polymers which are biodegradable have come increasingly to the fore. These may have to be treated with biocides to control the rate of breakdown. Conditioning agents that are particularly safe environmentally are those based on naturally occurring materials, such as Guar (also used as a slimming aid), Xanthan (a constituent of tomato ketchup) or locust bean gel (used in pet foods).

Foams are generally of low toxicity, although glycol-based foaming agents require extensive health and safety precautions and pose considerable constraints on disposal. A variety of commercial foams have been assessed in terms of aquatic toxicity and biodegradability (Wilkinson 1994), because of their widespread use in firefighting. Protein foams were generally found to be less toxic and more rapidly degradable than synthetic detergent foams. However wide variations were found between foams of similar types produced by different manufacturers and more information needs to be provided by the producers. Fluorocarbons in foams tend to be very persistent and are a potential problem for disposal of muck. The fluorocarbons are primarily needed for fire resistance, and foams for tunnelling are probably better without them.

Of the solvents used, hexylene glycol is of very low toxicity to fish. Ethylene glycol ethers used in synthetic foams are of higher toxicity. Some foams contain zinc salts which are potentially a problem. The small quantities of biocides used are unlikely to cause problems.

7. CASE STUDIES

The first major reported use of foam in Europe was on the Passante Ferroviario project in Italy (Peron and Marcheselli 1994). This was a 2000m long tunnel of excavated diameter 8.0m through alluvial sandy and gravelly soils, above the water table but with relatively low cover. Fines in the soil amounted typically to about 20%. The foam system used was that developed by Obayashi in Japan, and marketed in Europe by Lamberti CMC. The proportions of the foam mix were typically 1.5% foaming agent and 0.7% cellulose polymer stabiliser in water, and the foaming ratio in the range 5 to 8 depending on the nature of the ground (presumably thicker foam in coarser soils). For a foam ratio of 7 under an ambient absolute pressure of 1.9 bar in the muck chamber, the calculation of material quantities proceeds as follows:

Foaming agent 1.5l + polymer 0.7kg + water 97.8l
÷foaming solution 100l + air at 1.9 bar 600l (= air at 1 bar 1140l) ÷foam 700l

The foam injection or mixing ratio used was 60 to 80%, and in the dry soils 5% of water was also added. For part of the drive excavation was in water-bearing ground, and it was then possible to reduce the foam injection ratio to 50 to 60%. The slump of the muck was kept between 5 and 10cm.

Use of foam conditioning for an EPBM drive in Valencia, for part of Line 5 of the Metro, is described in an article by Wallis (1995); further details of the same project are provided by Herrenknecht and Maidl (1995). The tunnel bore was 6.52m and the drive mainly through alluvial sands and gravels with typically about 15% fines, with some lenses of stiff silty clay. The tunnel was below the water table, and the permeability of the ground high to very high, with quoted coefficients of permeability of 10^{-4} to 10^{-3} m/s. An EPBM shield was chosen in preference to a slurry shield because of potential problems with loss of slurry in lengths of tunnel above the water table and the difficulty and expense of separating clay and silt from the slurry, and because the EPBM provided certain protection against a large-volume collapse at the face. The shield was fitted with injection ports for both bentonite and foam, and initially the use of bentonite was preferred. However it was found that the shield was difficult to operate due to the variations of pressure within the head chamber. Use of foam produced a more homogeneous and compressible material and overcame the problems. Foam was injected through the cutting wheel, through the chamber bulkhead, into the screw conveyor and through the skin of the shield. Compressed air pressure of 6 bar was used to generate a foam with a working pressure of about 2.5 bar. Foam consumption was about 25-35% of the excavation volume, with the amount of foaming agent used being varied to alter the foam density and bubble strength to match the ground and groundwater conditions. Reductions in the drive torques for the cutting wheel and screw conveyor of about 20% are quoted.

A North-American experience is reported by Webb and Breeds (1997). A tunnel 2 miles long (3.2km) of diameter 157 inches (4m) was driven through very mixed ground conditions with cover of 15 to 400 feet (4.6 to 122m) and water head of up to 60 feet (18.3m). A muck-stiffening (water-absorbing) polymer additive at rates of 0.5% to 2.0% by volume in water were used, the amount increasing with the coarseness of the soil; concentrations of 4 to 10% were used locally for sealing off excessive water flows. Foam and occasionally bentonite were also used as required. The use of additives allowed the tunnel to be driven in semi-EPB mode, with flood doors and pressure relief gates but no screw conveyor.

Mauroy (1998) reports on the use of EPBMs with foam conditioning for construction of sections of the underground guided transit lines in Lille. These involved excavation of 7.7m diameter tunnels through Flanders clay. The EPBMs were equipped with 6 points for injection of foam (or other liquid) on the cutter head, 12 points on the chamber bulkhead, and 2 on the screw conveyor. Initially only two foam injectors fed the cutter head points, whereas other points were each fed by an individual injector. After initial problems, this was changed so that 8 injectors fed the cutter head, thereby concentrating injection at the front of the machine. Foam concentrations were varied, and an optimum expansion ratio of 20 eventually chosen. Bulking of the excavated soil in the chamber was allowed, thereby producing a compressible material which evened out pressure variation. It was found that best control of the earth balance pressure was obtained by monitoring the pressure at the top of the chamber bulkhead where pressure fluctuations were least. Babendererde (1998) reports, apparently with reference to the same project, that use of soil conditioning reduced the cutterhead torque from 900 to 400tm and the thrust forces from 2000 to 1200t.

Doran and Athenoux (1998) discuss the selection and operation of the TBM for the Storebaelt tunnel in Denmark. The EPB shield chosen experienced great problems in the glacial tills with water-bearing lenses under high pressure (2.2 bar) and very hard clays with a highly fractured structure. There were no facilities to promote proper mixing of cut soil in the chamber, though water and polymer could be injected through ports in the pressure bulkhead and into the screw conveyor. Controlling the water content in the low-plasticity clay was extremely difficult; serious problems were also encountered with excessive machine wear. Addition of foam and polymer was considered, but foam was thought to be unreliable under the high pressures at the face, and there were problems in introducing polymer and mixing it effectively with the soil. The authors conclude that a machine able to operate in slurry mode would have been preferable in some of the ground conditions encountered, and that provision of ports for injection of water or other agent ahead of the drag bit locations on the cutter head would have been necessary, and mechanical mixing essential for the use of polymers.

Foam is known to have been used or is currently being used on many projects in the UK employing EPB shields, but details are either not available or are being treated as confidential at present. Similar comments apply to the Toronto subway project in Canada. Slurry shields have or are being used with bentonite slurries with polymer additives at a number of projects in the UK, but results have not yet been reported.

8. RESEARCH

While soil conditioning agents have been in use for a number of years in a number of countries, relatively little research appears to have been done on the basic properties of conditioned soil and the requirements for satisfactory performance in different situations, most notably in EPB tunnelling shields. Where investigations have taken place, they have usually been done by individual contractors in attempts to find answers to particular problems. Results of these investigations are usually not published.

In recent years work has been undertaken on the use of foams in EPB shields at Bochum University in Germany (Maidl (1995)), at Lille University in France (Quebaud (1996)), and at Delft Geotechnics in the Netherlands (Bezuijen et al. (1999)). The work in France has been undertaken as part of the French National Project on Microtunnels. This project also includes work on the lubrication of pipe jacks, which is being undertaken at the National Institute for Applied Sciences (INSA) in Lyon. The pipe jacking research project at Oxford University has also included measurements of the effects of lubrication. Findings from all these projects have been published and results from them have been drawn on for the sections above. A new project which started in the autumn of 1998 at Oxford University and in 1999 at Cambridge University is directed at investigating soil conditioning and lubrication with various materials including foam, polymers and bentonite. It is intended to correlate results from laboratory tests with data from active tunnelling projects, with the aim of arriving at a set of tests suitable for checking which conditioners are most appropriate for various ground conditions.

Further research is needed in a number of areas, of which the following are suggested (in no particular order) as being of greatest urgency:-

- mechanics of injection processes at tunnel face, interaction of flows of additive, cutting action of tools etc
- mechanics of mixing in the machine head chamber, where best to add materials and how to optimise mixing processes, effects of earth balance pressures and water inflows
- suitable test procedures for assessing the effectiveness of conditioning agents in different ground and groundwater conditions, for site control and choice of dosage rates etc.
- use of foam under severely adverse conditions of ground permeability, water pressures, earth balance pressures etc.
- investigations of the health and safety and environmental consequences of the use of conditioning agents throughout the tunnelling process
- further investigations of the most effective and economical lubricating fluids for pipe jacking in different ground conditions.
- methods of anticipating changes in soil conditions at the face so that lubrication and soil conditioning may be tailored accordingly
- control systems to maximise the benefits of conditioning agents being added in conditions of variable advance rate
- investigating the risks and appropriate action to be taken when a tunnelling machine using conditioning is forced to stop.
- design of appropriate additive schemes for mixed face ground conditions.

Until results of further research become available, advances in the effective use of lubrication and conditioning could be made on an empirical basis through pooling of practical experience under different conditions.

9. SUMMARY

A wide range of possible materials and applications has been reviewed in this report. The applications may be summarised briefly as follows:-

For slurry tunnelling, bentonite slurries, if necessary with polymer additives to enhance formation of a filter cake, maintain dispersion and provide lubrication; polymer flocculating agents to improve performance of separation plants.

For 'lubrication' of pipe jacks, bentonite slurries, if necessary with additives to inhibit swelling of clays, improve filter cake formation and increase lubricity. It is possible that foam might also be used in this situation, but as yet no information is available concerning its effectiveness.

For tunnelling with EPBM shields, a wide range of conditioning agents from water through bentonite slurries to various polymer materials and especially foams, injected at the face, in the working chamber or in the screw conveyor. Tunnelling machines must be provided with adequate facilities for adding the agents in controlled dosages and ensuring that they are sufficiently mixed with the soil, and additives need to be correctly chosen for the types of soil encountered.

Much further research, development and practical experience is needed to ensure that the benefits of soil conditioning, potentially very great, are fully realised in practice.

10. ACKNOWLEDGEMENTS

This review was commissioned and the costs of its production covered by the Pipe Jacking Research Group, a consortium comprising the Pipe Jacking Association, North West Water, Thames Water and Severn Trent Water. The support of these organisations is gratefully acknowledged; their representatives on the research management group were

Arthur Moss, Tunnel Management Systems, PJA, chairman of the management group
Doug Allenby, Edmund Nuttall Ltd., PJA chairman
David Cook, Bechtel Water Technology for North West Water
John Greenwood, Thames Water Utilities
Geoff Bateman, Charles Haswell and Partners for Severn Trent Water

John Lyon of CETCO Europe Ltd. has provided invaluable advice and information and has been co-opted onto the management group. CETCO also kindly provided some cash input to the project and undertook the preparation of some of the figures. Useful meetings were also held with Martin Herrenknecht of Herrenknecht GmbH and Adam Bezuijen of Geodelft (formerly Delft Geotechnics), who provided information on work on soil conditioning in Germany and the Netherlands. The author is grateful to all those who provided comments on the drafts of the document, in particular Arthur Moss, Doug Allenby, Robert Mair of the Geotechnical Consulting Group, Fin Jardine of the Construction Industry Research and Information Association (CIRIA), and Stephan Jefferis of Golder Associates.

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12. GLOSSARY

Activity — the ratio of *plasticity index* to clay content for a clayey soil; a high activity generally indicates a high proportion of *montmorillonite*

Anionic — having a negative ionic charge

Band filter — see *belt filter press*

Belt filter press — a system for reducing the water content of sludge in a separation plant by compression of the material between filter belts as they pass around a set of rollers; alternatively called a *belt press, belt filter* or *band filter*

Belt filter — see *belt filter press*

Belt press — see *belt filter press*

Bentonite — highly plastic *colloidal* clay, primarily made up of the mineral sodium *montmorillonite*

Bingham fluid — a fluid in which the resistance to shear flow increases linearly with flow rate from a finite value (*yield point*) at zero flow rate (Cf. *Newtonian fluid*)

Cationic — having a positive ionic charge

Centrifuge — a piece of equipment used to reduce the soilds content of the slurry in a separation plant; the slurry is rotated at high speed and the solids driven to the outside by centrifugal action. A centrifuge is effective on smaller particle sizes than a *hydrocyclone*

CMC — abbreviation for **carboxymethyl cellulose**, one of a range of *polymers* which find a use in tunnelling and *pipe jacking*; for details see the text of the report

Coagulation — formation of compact aggregation of particles

Colloidal — a state of subdivision in which the particles, droplets or bubbles dispersed in another phase have a maximum dimension of one micron

Conditioning agent — a material used to improve one or more of the soil properties or aspects of soil behaviour relevant to its support, excavation, transport, removal or disposal

Copolymers — polymers achieved by combining two or more different types of *monomer*

Cutter head — a tool or system of tools mounted on a common support which excavates at the face of a tunnel

Cutting wheel — a cutter head of circular form is sometimes called a cutting wheel

Dispersion	state of a clay slurry in which the particles remain separated rather than *flocculated* or *coagulated*
Drainage time	a measure of the stability of a *foam*; the time required for a sample of foam to lose 25% of its initial volume (see also *half-life*)
EPBM	abbreviation for **earth pressure balance machine**, a type of *TBM* in which mechanical pressure is applied to the tunnel face through the excavated material in the *pressure chamber* and controlled to provide the correct counterbalance to the earth pressure in the ground to prevent settlement or heave
Excavation chamber	see *pressure chamber*
Expansion ratio	the ratio of the volume of *foam* to the volume of liquid used to produce the foam
Flocculant	a substance which promotes *flocculation*, usually with the aim of increasing the sedimentation rate of a *slurry*
Flocculation	formation of a loose network of particles (usually by bridging)
Foam	a dispersion of gas (usually air) bubbles in a liquid or solid in which at least one dimension falls within the *colloidal* size range
Foaming agent	any substance which aids the formation or stabilisation of a *foam*
Gel strength	the shear stress needed to initiate flow in a (gelled) *slurry* at rest; for an ideal *Bingham fluid* the gel strength and *yield point* are the same
Grizzly bars	bars across the openings in the *cutter head* of a tunnelling machine which are spaced to limit the maximum size of particle which may enter the *pressure chamber*
Half-life	a measure of the stability of a *foam*; the time required for a sample of foam to lose 50% of its initial volume (see also *drainage time*)
Head chamber	see *pressure chamber*
Homopolymer	*polymer* achieved by *polymerisation* of a single basic *monomer* unit
Hydrocyclone	a piece of equipment used to reduce the solids content of the slurry in a separation plant; operates on the principle of a *centrifuge* with the centrifugal effect generated by the flow of the fluid inside the hydrocyclone body
Hydroshield	a type of *slurry machine* in which an air bubble within the machine *head chamber* helps to stabilise the slurry pressure and compensates for imbalances in excavation and spoil removal rates
Illite	a clay mineral similar to *montmorillonite* but of much lower *activity*
Inhibition	use of a *conditioning agent* to prevent hydration and hence expansion of swelling clays
Lamella	(plural lamellae) the thin liquid film separating the gas bubbles in a *foam*
Liquid limit	the water content (in %) of a clay as it changes from a plastic solid to a viscous liquid
Liquidity index	the natural water content of a clay expressed as a figure on a linear scale between zero at the *plastic limit* and 1.0 at the *liquid limit*; given by (natural moisture content (%) - *plastic limit*)/*plasticity index*
Marsh funnel	an instrument used to assess the relative *viscosity* of *slurries* by measuring the time for a standard volume of liquid (1.0 litre or 1.0 US quart) to flow out of a standard shaped funnel
Methylene bridge	a link between long-chain *polymer* molecules formed by the methylene group CH_2=
Microtunnelling	in the UK is a term used for *pipe jacking* of pipes less than about 1000mm internal diameter (non man-entry sizes); elsewhere, particularly in the USA, it may be used to refer to pipe jacking at any pipe diameter which employs a remotely-controlled mechanised tunnelling shield
Mixing ratio	the volume of *foam* used as a *conditioning agent* as a proportion of the volume of soil excavated
Monomer	the small molecular unit from which a *polymer* is formed
Montmorillonite	one of the smectite group of clay minerals, which are hydrated aluminium silicates
Newtonian fluid	a fluid in which the *viscosity* is independent of the rate of shear (flow); the shear resistance increases linearly with flow rate from zero at zero flow rate (Cf. *Bingham fluid*)
PA	abbreviation for **polyacrylamide**, one of a range of *polymers* which find a use in tunnelling and *pipe jacking*; for details see the text of the report

PAC	abbreviation for **polyanionic cellulose**, one of a range of *polymers* which find a use in tunnelling and *pipe jacking*; for details see the text of the report
pH	a measure of the acidity or alkalinity of water on a logarithmic scale; neutral water has a pH of 7, smaller values indicate acidity and higher values alkalinity
PHPA	abbreviation for **partially hydrolysed *polyacrylamide***, one of a range of *polymers* which find a use in tunnelling and *pipe jacking*; for details see the text of the report
Pipe jacking	a technique for installing underground pipes or ducts in which the pipes are pushed through the ground behind a tunnelling shield using hydraulic jacks reacting against a thrust wall in a jacking or thrust pit
Plastic limit	the water content (in %) of a clay as it changes from a plastic solid to a brittle solid
Plasticity index	the difference between the *liquid limit* and the *plastic limit* for a clay
Plateau border	the transition region at the junction between thin films (*lamellae*) in a *foam*
Polymer	a large molecule built up by repetitive bonding together (*polymerisation*) of many smaller molecules, called *monomers*
Polymerisation	the linking together of small chemical 'building blocks' (*monomers*) to form large, long-chain molecules called *polymers*
Porosity	the ratio of pore volume to total volume in a soil
Pressure bulkhead	a bulkhead in a tunnelling machine or shield separating the pressurised *working chamber* from the remainder of the machine or shield
Pressure chamber	the chamber in a tunnelling machine behind the *cutter head* containing pressurised slurry (in a slurry machine) or excavated material (in an earth pressure balance machine); variously referred to as *head chamber*, *working chamber*, *excavation chamber*, *slurry chamber*
Rheology	the science dealing with the behaviour of fluids undergoing deformation
Screw conveyor	a spiral auger, with or without a centre shaft, rotating within an outer casing, used to convey excavated material at a controlled rate from the *pressure chamber* of an *EPBM*
Slurry	oil- or water- based fluid containing suspended solids used to provide fluid pressure and spoil transport in slurry tunnelling machines, and lubrication and soil conditioning in all forms of mechanised tunnelling and pipe jacking
Slurry machine	type of *TBM* in which the earth and groundwater pressures are counterbalanced by pressurised slurry to prevent heave or settlement
Slurry chamber	see *pressure chamber*
Surface tension	generally the force per unit length acting within the interface between a liquid and its own vapour or air, which te.nds to maintain the area of the surface at a minimum
Surfactant	a substance that tends to concentrate at an interface (e.g. between liquid and air) and modify the properties of the interface, for example by changing the *surface tension* and allowing bubbles (foam) to form more readily (see also *tenside*)
TBM	abbreviation for **tunnel boring machine**; a full-face circular mechanised shield machine, usually of man-entry diameter, steerable and with a rotary *cutter head*
Tenside	an alternative word for *surfactant*
Thixotropy	the ability of a fluid to to develop *gel strength* with time, allowing it to form a rigid structure which can be returned to the fluid state by mechanical agitation
Viscometer	an apparatus for measuring the *viscosity* of a liquid at different rates of shear (flow)
Viscosity	a measure of the (shear) resistance to flow of a liquid
Working chamber	see *pressure chamber*
Yield point	the shear resistance of a *slurry* at zero flow rate, usually determined by extrapolation to the zero axis from measurements made at two or more non-zero flow rates (see *Bingham fluid*, *gel strength*)

13. TABLES

Shield type			EPBM		Slurry
Soil type		SPT N	Without additives	With additives	
Alluvial cohesive Soil	Silt and clay	0 - 2	Y	Y	Y
	Sandy silt, sandy clay	0 - 5	Y	Y	Y
		5 - 10	Y	Y	Y
Pleistocene cohesive Soil	Loam and clay	10 - 20	**N**	Y	Y
	Sandy loam, sandy clay	15 - 25	**N**	Y	Y
		over 25	**N**	Y	Y
Sandy soil	Sand with silty clay	10 - 15	Y	Y	Y
	Loose sandy soil	10 - 30	**N**	Y	Y
	Consolidated sand	over 30	**N**	Y	Y
Gravel with boulders	Loose gravel	10 - 40	**N**	Y	Y
	Consolidated gravel	over 40	**N**	Y	Y
	Gravel with boulders	-	**N**	Y	**N**
	Boulder gravel, boulders	-	**N**	**N**	**N**

Table 1: Geotechnical selection chart for tunnel systems
(from Standard Specification for Tunnels, Japanese Society of Civil Engineers, 1996)

Location	Open or closed face TBM[1]	Slurry shield/mix shield machines	EPBM[2]
Tunnel face	Lubricate cutters and spoil; reduce wear and power requirements	Improve slurry properties to provide optimum filter cake in soil; reduce wear and power requirements	Lubricate cutters and spoil; reduce wear and power requirements; permeate soil face and reduce water inflows; start process of modifying excavated material
Machine head	Improve muck flow through head; reduce friction and wear	Prevent clogging with plastic clays; reduce wear with abrasive soils	Help soil to obtain a plastic state of suitable consistency; prevent re-compaction of plastic clays; prevent clogging; reduce friction and wear; provide compressible material to reduce pressure fluctuations
Spoil handling system	Reduce water content to improve handling	Improve dispersion of excavated soil in slurry; reduce wear with abrasive soils; improve performance of separation plant	Produce suitable plastic state in spoil for controlled flow through screw conveyor; reduce permeability of spoil to prevent excessive water flow through screw conveyor; reduce friction, wear and power requirements for screw conveyor; reduce water content of muck for easy handling
Spoil tip	Improved spoil quality for easier disposal or re-use for construction purposes	Improved spoil quality for easier disposal or re-use for construction purposes	Improved spoil quality for easier disposal or re-use for construction purposes
Tunnel bore	Use in slurry to support tunnel bore and provide lubrication of pipes in pipe jack construction	Use in slurry to support tunnel bore and provide lubrication of pipes in pipe jack construction	Use in slurry to support tunnel bore and provide lubrication of pipes in pipe jack construction

1. TBM = tunnel boring machine 2. EPBM = earth pressure balance machine

Table 2:Possible applications of soil conditioning in tunnelling machines

Soil type	Mining characteristics	Treatment	
Plastic clays	Tend to reconstitute with little loss of strength in machine chamber.	High dosage of foam at head to keep excavated material as separate pieces.	
Laminated, silty or sandy clays	Break up better, but still tend to re-constitute, slightly abrasive, form plug.	Possibly none other than water to reduce shear strength to acceptable value; in stiffer clays, medium dosage of foam at head. Possibly add lubricant to foam to reduce abrasion.	
Clayey sands and gravels.	Flow easily, may form plug if fines content in excess of 10%; highly abrasive.	Add lubricant polymer at head to reduce wear; add water-absorbing polymer at screw if required to form plug and control water inflow.	
Silty fine sands	Do not flow, do not form plug, allow ground water inflow, highly abrasive; problems increase with larger particle sizes.	Foam with polymer additive to stiffen foam and provide lubrication; approximate dosage rates for polymer:-	0.1%
Sand/gravel			0.25%
Gravel and cobbles			1 - 3%
Cobbles and boulders	Tend to congregate in clumps in head and/or jam screw.	Large dosages of additive to keep cobbles separate in head and provide water control and lubrication.	

Table 3:Summary of use of soil conditioning in EPB machines (after Morrison (1997))

14. APPENDIX: TEST PROCEDURES

1. *Viscosity of slurry using Marsh funnel*

The Marsh funnel is 6" (150mm) in diameter at the top, tapering over a distance of 12" (300mm) distance to a smooth bore tube 2" (50mm) long with an inside diameter of 3/16" (4.8mm). Near the top, over half the top opening, is a wire screen with apertures of 1/16" (1.6mm).

i. hold the funnel upright with one finger over the bottom opening, pour the slurry sample through the screen (to remove cuttings and other material which might block the funnel) until the fluid level reaches the bottom of the screen (1500ml).
ii. remove finger from the outlet and measure the time on seconds for the slurry to fill a vessel of volume one American quart (946ml) or one litre.
iii. record the temperature and report the Marsh funnel viscosity in secs/qt (secs/litre).

2. *Sand content of slurry.*

The instrument consists of a 2.5" (63.5mm) diameter sieve with a 200 mesh (0.075mm) screen, a funnel to fit over the sieve and a glass measuring tube, marked for the volume of slurry to be added in order to read the percentage of sand by bulk volume directly from the tube (0-20%).

i. Fill the measuring tube to the indicated mark with slurry
ii. Add water to the next mark
iii. Close the mouth of the tube and shake vigorously
iv. Pour the mixture onto the screen a little at a time, add more water to the tube, shake and again pour onto the screen. Repeat until the wash water is clear.
v. Wash the sand on the screen to free it of any mud
vi. Fit the funnel over the top of the sieve. Invert slowly and insert end of the funnel into the mouth of the glass tube.
vii. Wash the sand into the tube by means of a fine spray of water.
viii. Allow the sand to settle. Read percent sand by volume from the gradations on the tube.

3. *Slurry weight or density*

The instrument used is called a mud balance and consists of a base upon which is balanced a graduated arm with a cup, lid, knife edge, level vial, rider and counterweight.

i. Completely fill the cup with slurry
ii. Replace the lid firmly, making sure that fluid is expelled through the hole in the top of the lid.
iii. Wash excess mud from the outside of the cup
iv. Place balance arm on fulcrum of base.
v. balance by moving rider until level on arms indicates level.
vi. Read slurry weight or density at the left hand edge of the rider.

The instrument is calibrated by filling with fresh water and adjusting a balance screw to give the correct reading.

4. *Method for the determination of foam expansion and drainage time (25%)*

See following two pages.

DEF STAN 42-40/1
ANNEX B

METHOD FOR THE DETERMINATION OF FOAM EXPANSION AND DRAINAGE TIME (25%)

B.1 Outline

This method describes the determination of foam expansion and drainage time (25%), using the concentrates specified in this Standard.

B.2 Apparatus

The apparatus shall consist of:

B.2.1 The equipment specified in Annex **A.**

B.2.2 A brass drainage pan, of 1630ml nominal volume known to ± 1% as illustrated in Figure 2. The centre of the conical base of the drainage pan is to be rounded to accept externally, a 12.7mm bore by 25mm long polymethyl methacrylate tube, which has a 1.6mm bore brass cock at its lower end.

B.2.3 A 100ml graduated measuring cylinder.

B.3 Prerequisites

B.3.1 Prepare a 10 litre sample of foam solution by mixing the appropriate concentrate with the appropriate water (potable and artificial sea water described in Annex F) in the proportion shown in Table C.

B.3.2 Wet the drainage pan internally, shake off excess water, shut the stop-cock and weigh (Wl).

B.4 Procedure

B.4.1 Produce foam as described in Annex A.

B.4.2 When the correct flow rate has been established and foam is being produced for at least 10 seconds, insert the drainage pan vertically in the foam stream for foam collection. Begin timing when foam enters the drainage pan.

B.4.3 When the drainage pan is full, remove it from the foam stream and expel any excess foam from the outside of the pan.

B.4.4 Weigh the drainage pan and contents (W2). Use this figure to calculate the expansion ratio **(E)** and the 25% drainage volume (D). The appropriate equations are shown in **B-5.**

B.4.5 Replace the drainage pan on its stand and position the graduated measuring cylinder beneath the stopcock. Then carefully open the stopcock to allow the flow of liquid to the measuring cylinder avoiding aeration. The flow should be regulated so that the liquid level in the drainage pan (visible through the polymethyl methacrylate tube) is just above the stopcock.

B.4.6 When the volume of liquid collected in the measuring cylinder is equal to the 25% drainage volume (D), stop timing and close the stopcock. Record the time as the 25% drainage time.

B.4.7 Measure the temperature of the foam remaining in the drainage pan and note.

B.5 Calculations

B.5.1 Calculate the expansion ratio (E) from the equation:

$$E = V/(W_2 - W_1)$$

where V = drainage pan volume in ml.
W_1 = mass of the empty drainage pan in grams.
W_2 = mass of the full drainage pan in grams.

B.5.2 Calculate the 25% drainage volume (D) from the equation:

$$D = V/(4 \times E)$$

where E = expansion ratio calculated at **B.5.1** above.
V = drainage pan volume in ml.

B.6 Report

Report the 25% drainage time, expansion ratio, 25% drainage volume and the foam temperature.

15. FIGURES

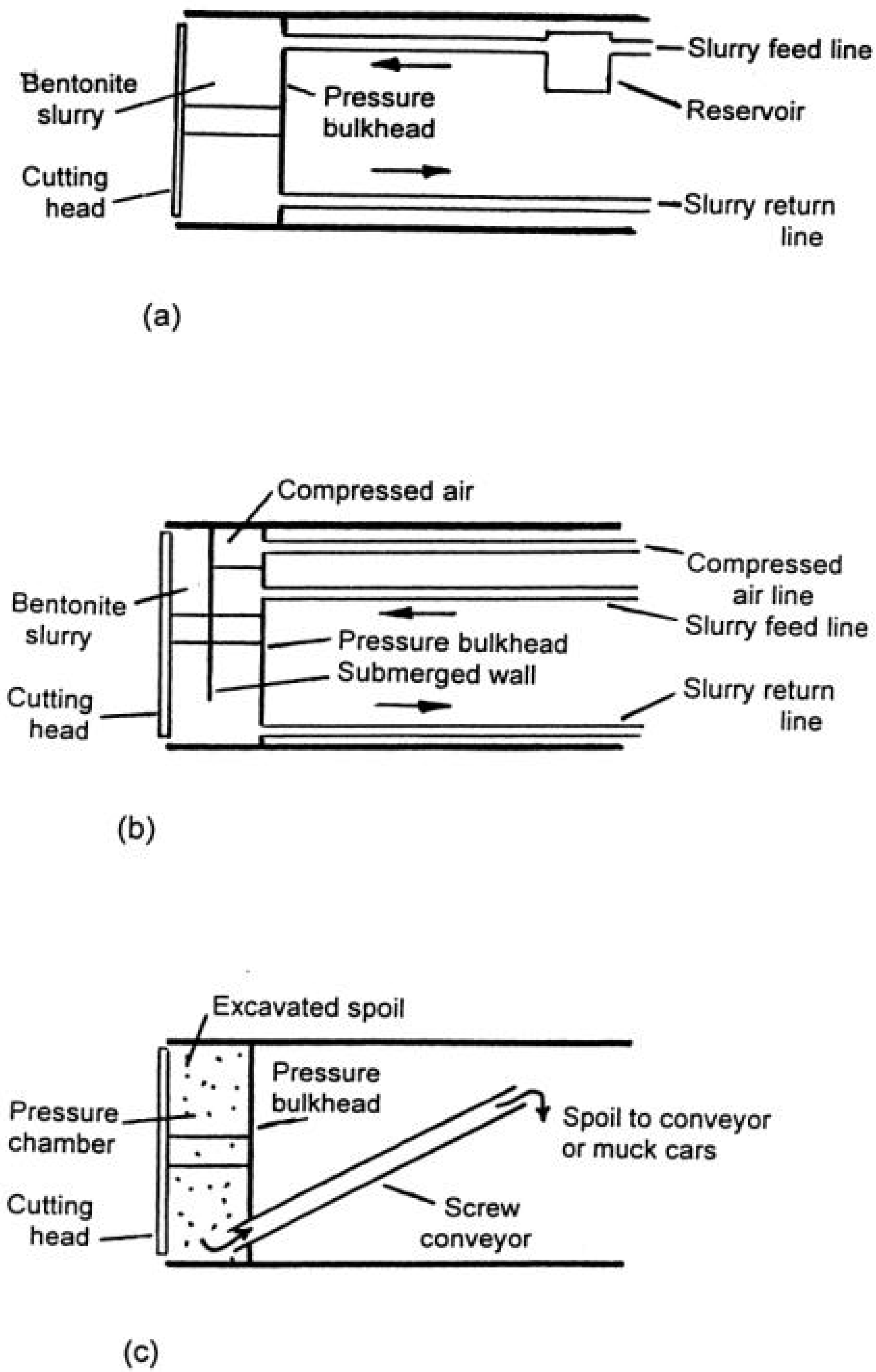
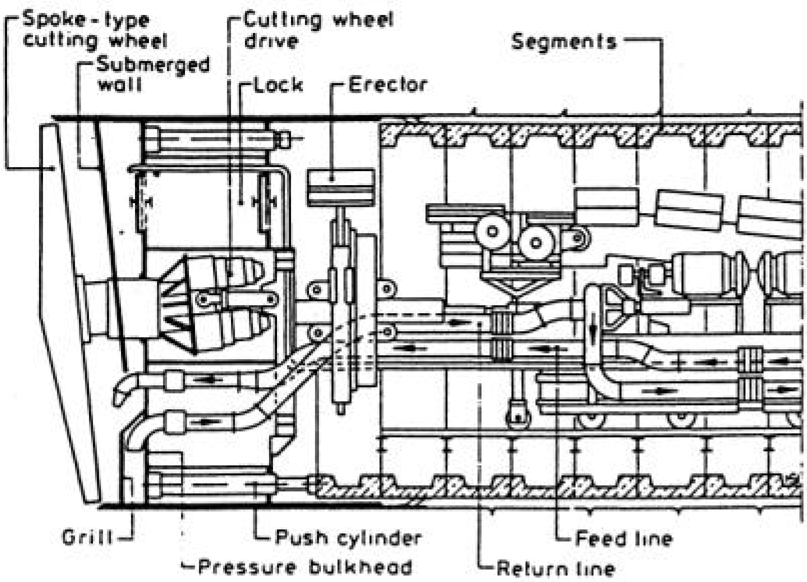
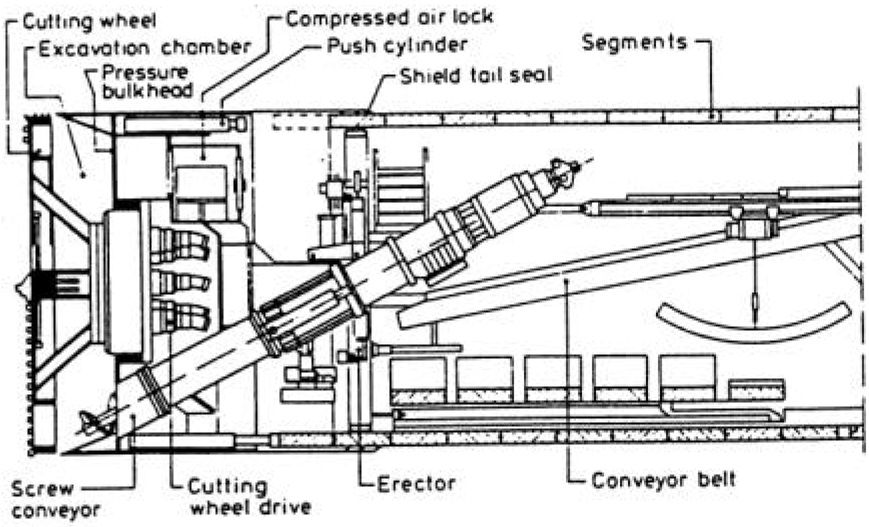


Figure 1 **Tunnelling shields (schematic)**
(a) Slurry shield
(b) Hydroshield
(c) Earth pressure balance shield



(a)



(b)

Figure 2 **Details of machines**
(a) Slurry shield (hydroshield)
(c) Earth pressure balance shield
[from Maidl et al. (1996)]

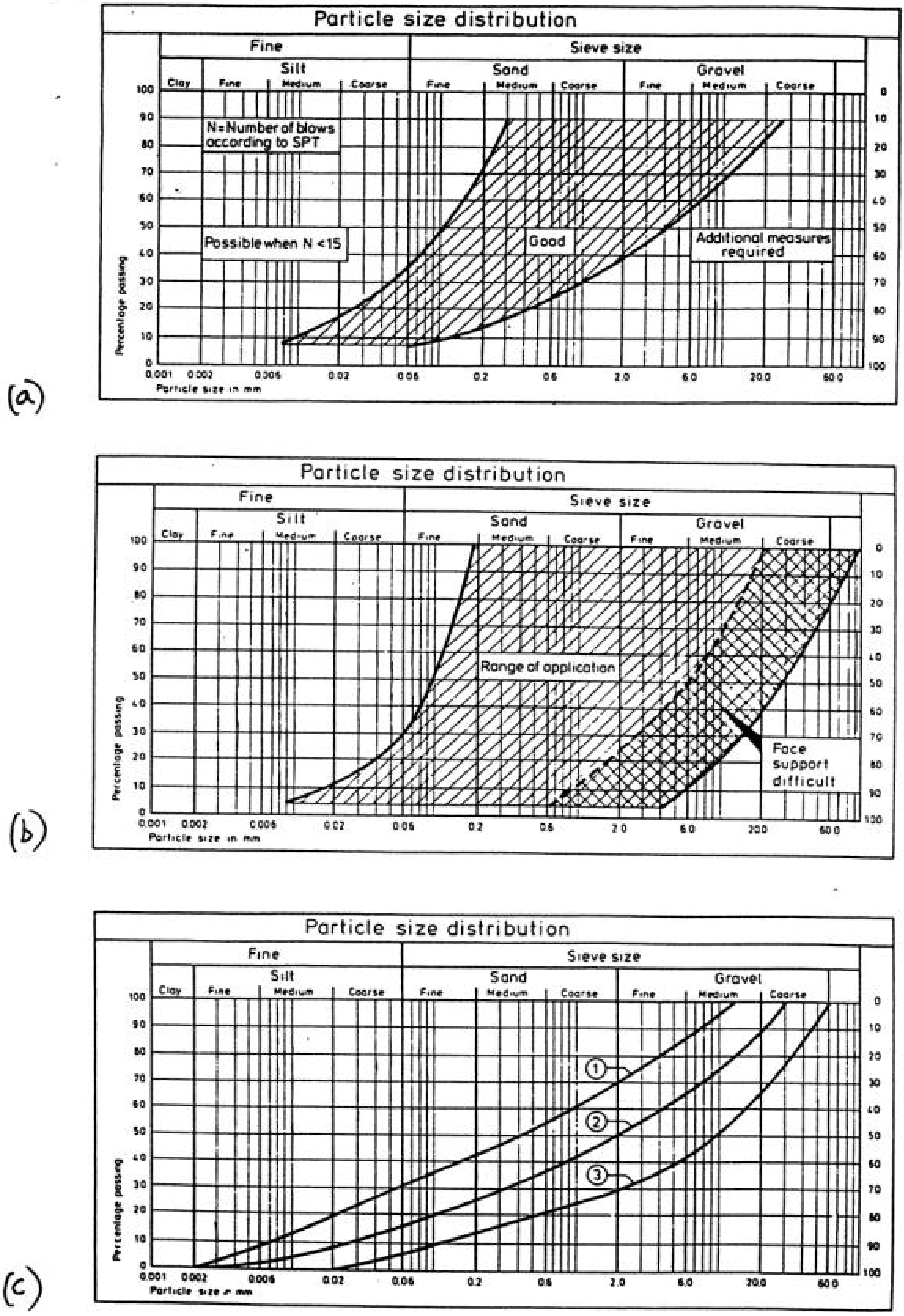


Figure 3 **Soil gradings for different types of tunnelling machine**
(a) Slurry shield (b) Hydroshield (c) EPB shield
[from Maidl et al. (1996)]

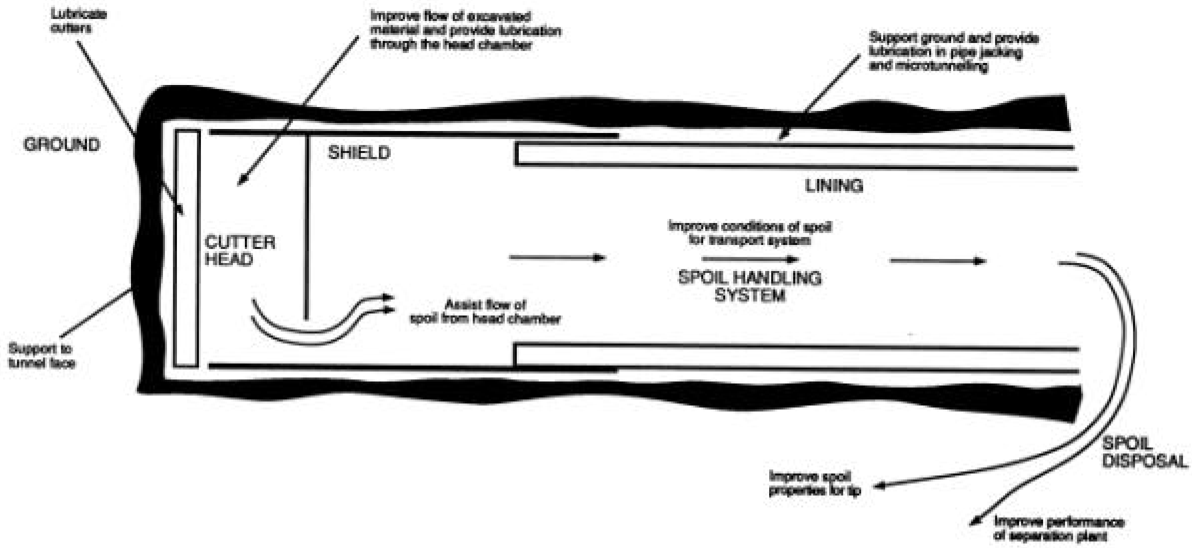


Figure 4 Uses of soil conditioning

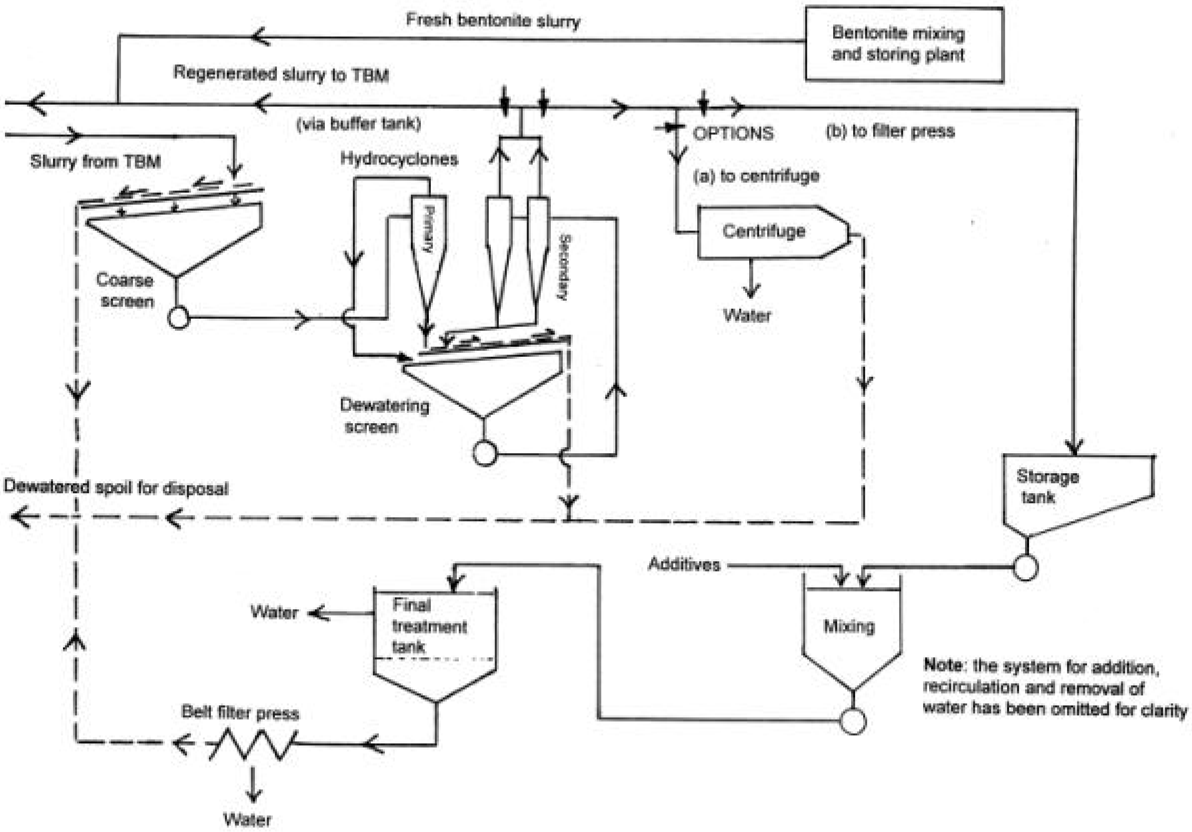


Figure 5 Simplified flow diagrams for typical separation plants
(a) using vibrating screens, hydrocyclones and centrifuge
(b) using a belt filter press in place of a centrifuge

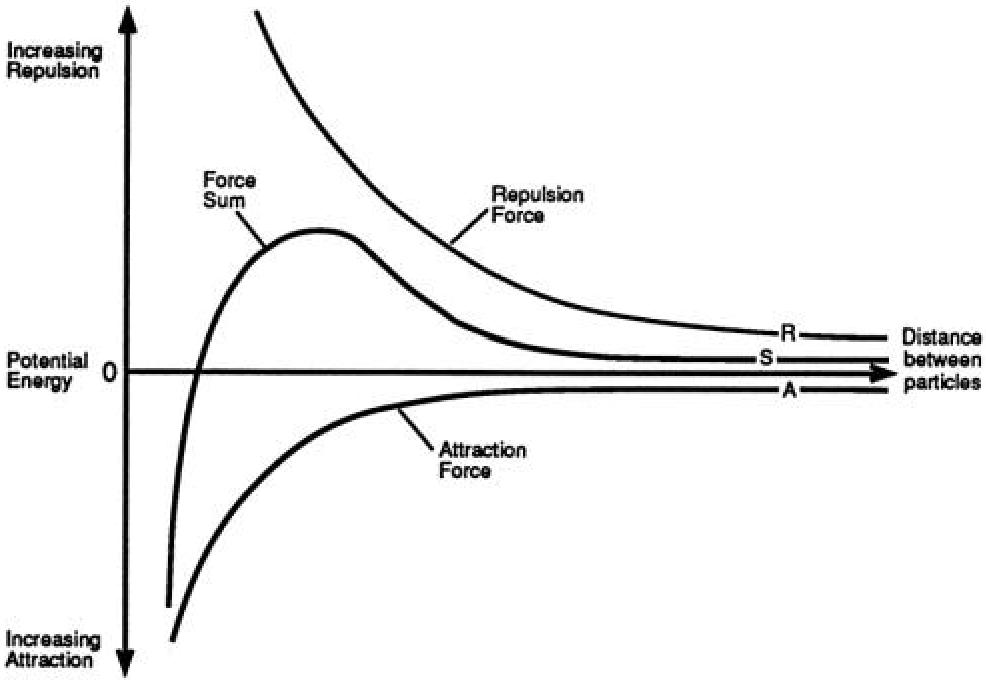


Figure 6 **Short-range forces between particles**

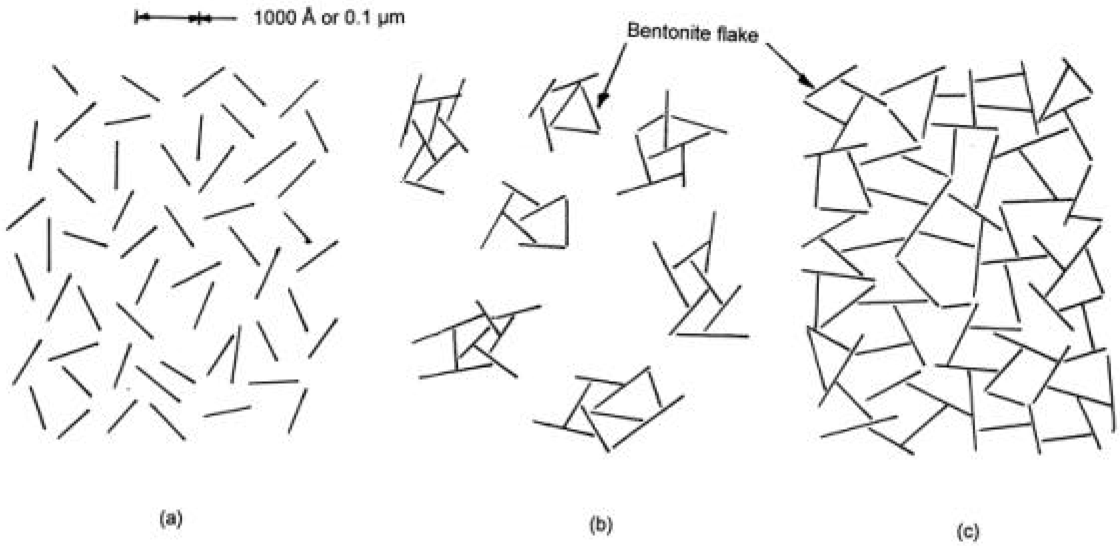


Figure 7 **Structures of bentonite slurry (a) Dispersed (b) Flocculated (c) Gel**

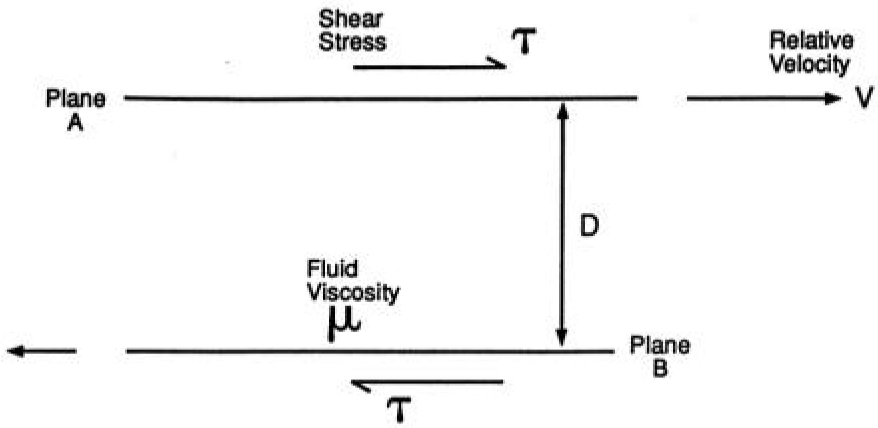


Figure 8 **Definition of viscosity**

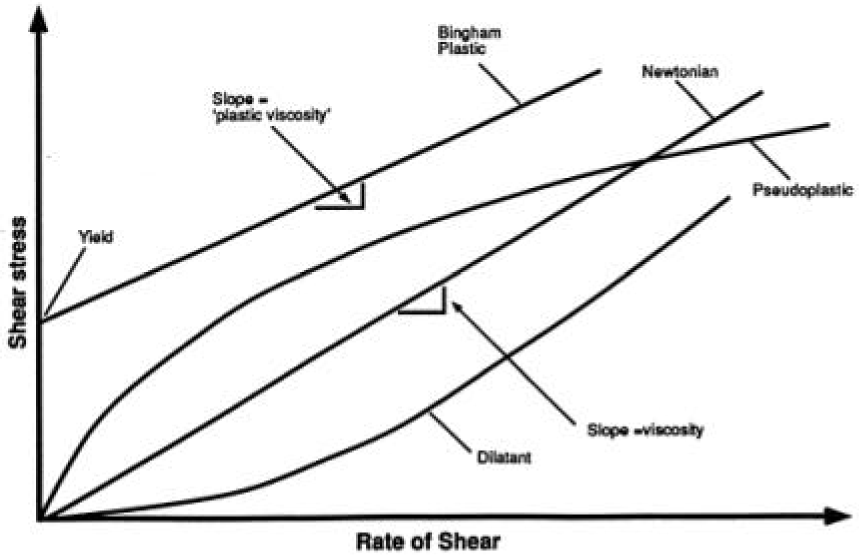


Figure 9 Models of viscous behaviour

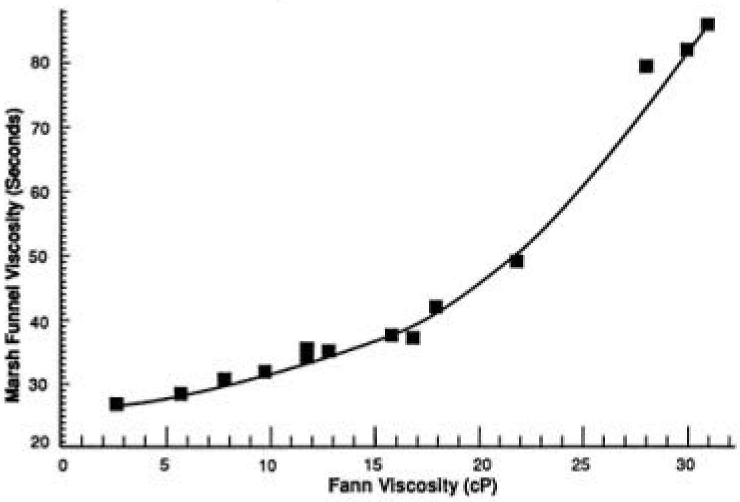
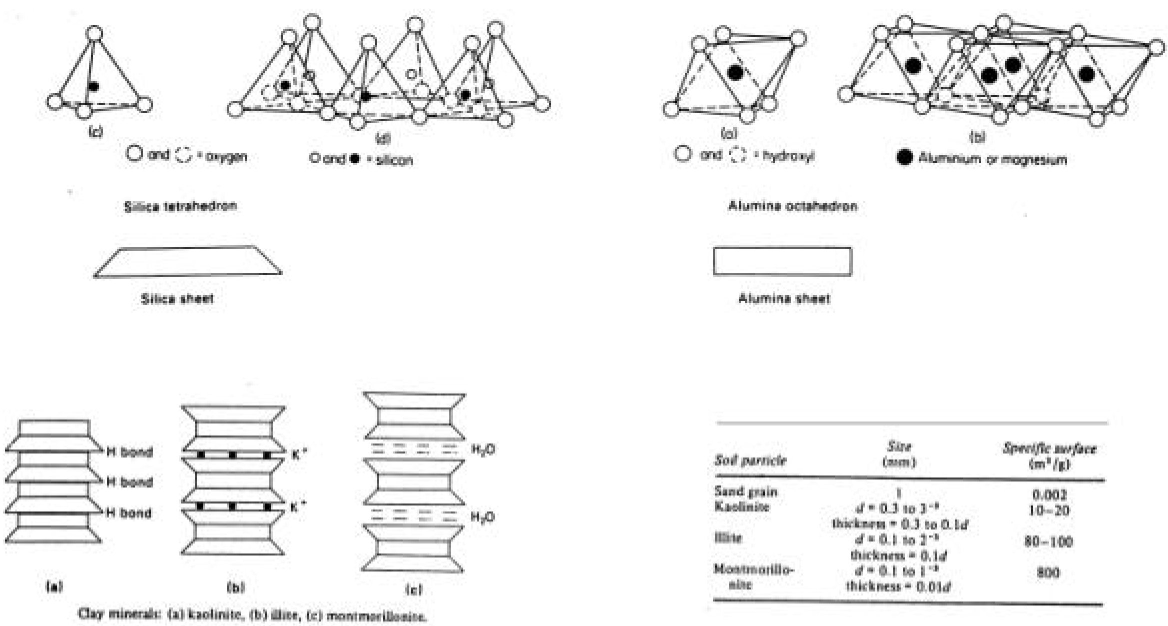


Figure 10 Relation between results from Marsh funnel and Fann viscometer



Soil particle	*Size* (mm)	*Specific surface* (m^2/g)
Sand grain	1	0.002
Kaolinite	d = 0.3 to 3^{-3} thickness = 0.3 to 0.1d	10–20
Illite	d = 0.1 to 2^{-3} thickness = 0.1d	80–100
Montmorillo-nite	d = 0.1 to 1^{-3} thickness = 0.01d	800

Figure 11 Structure of clay minerals

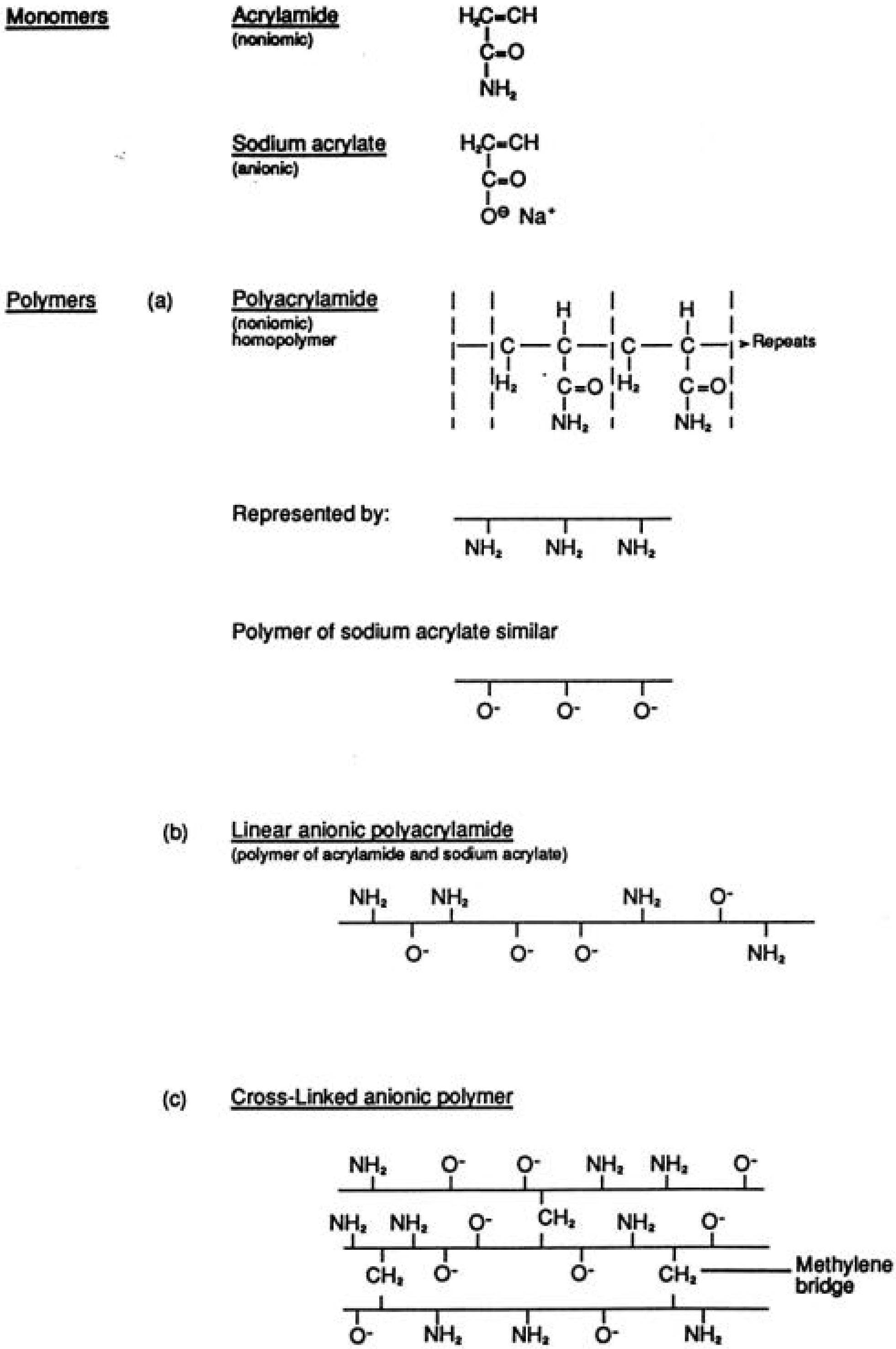


Figure 12 Formation of polyacrilamide polymes
(a) non-ionic (b) anionic (c) cross-linked

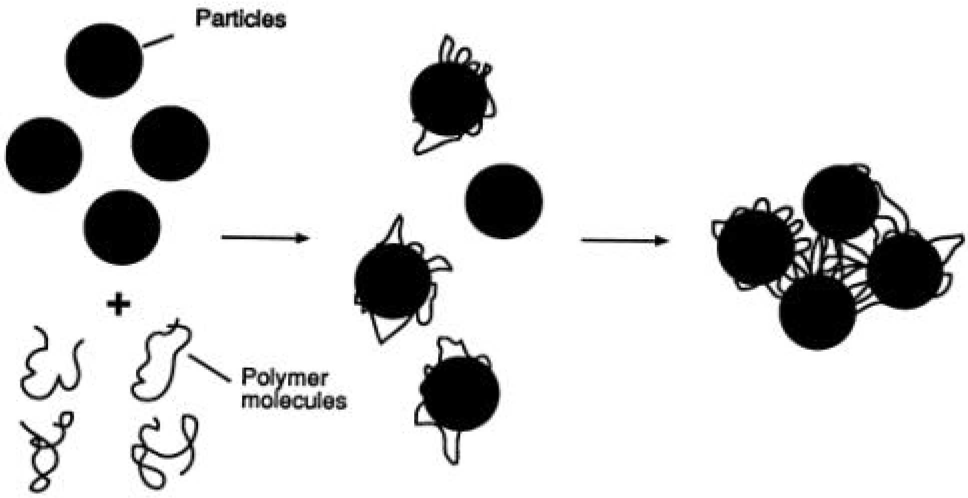


Figure 13 Bridging mechanism of flocculation

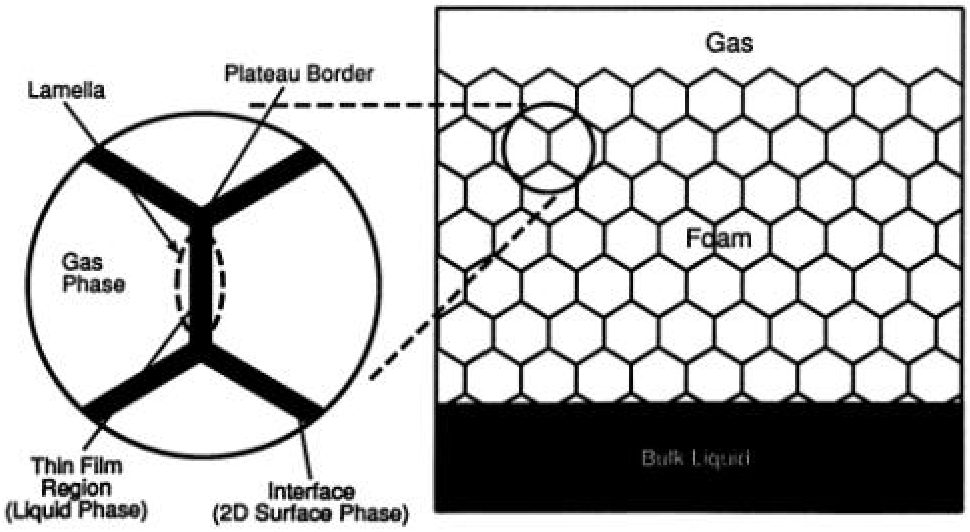


Figure 14 Structure of foam

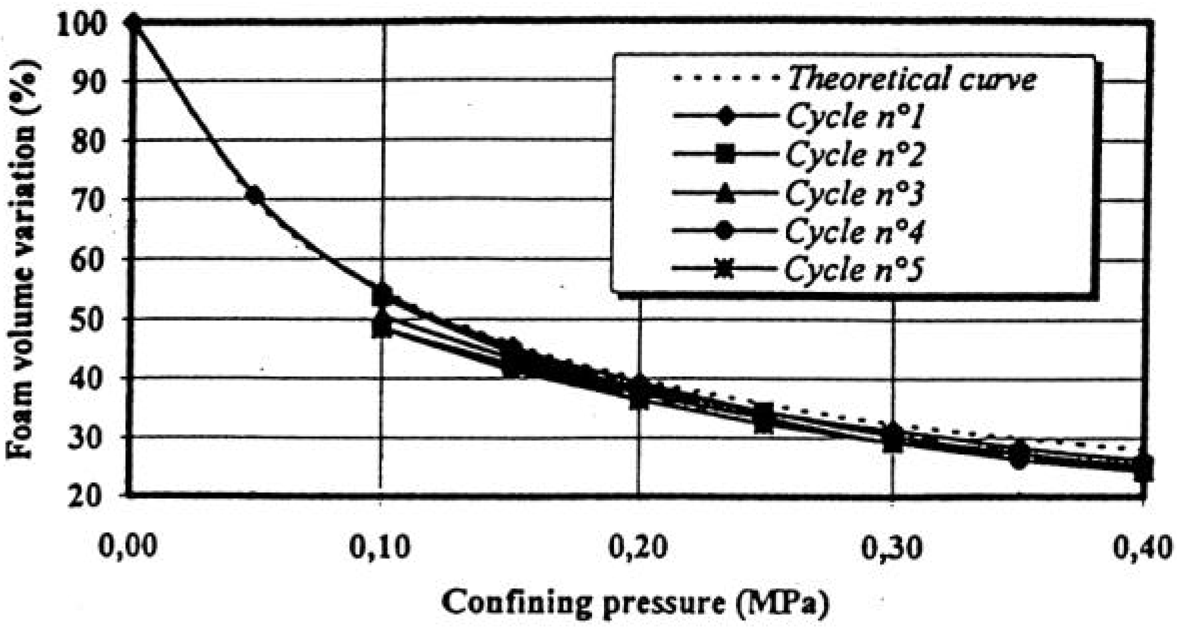


Figure 15 Results of foam compression test [from Quebaud et al. (1998)]

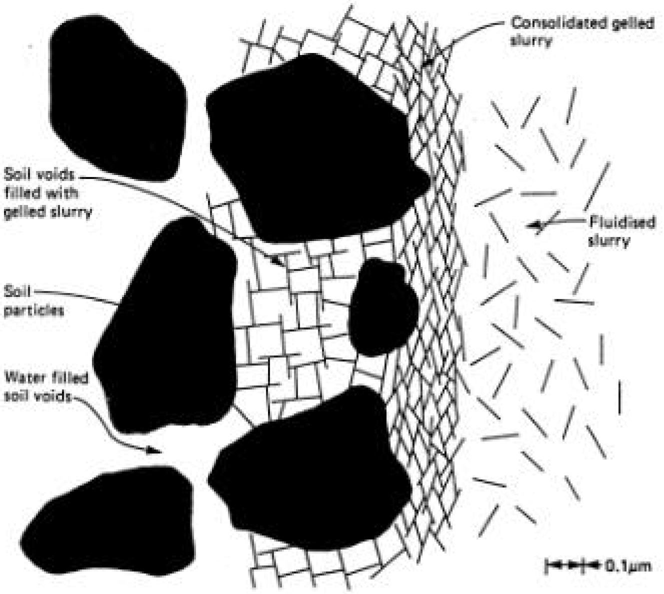


Figure 16 Formation of filter cake [from Washbourne (1986)]

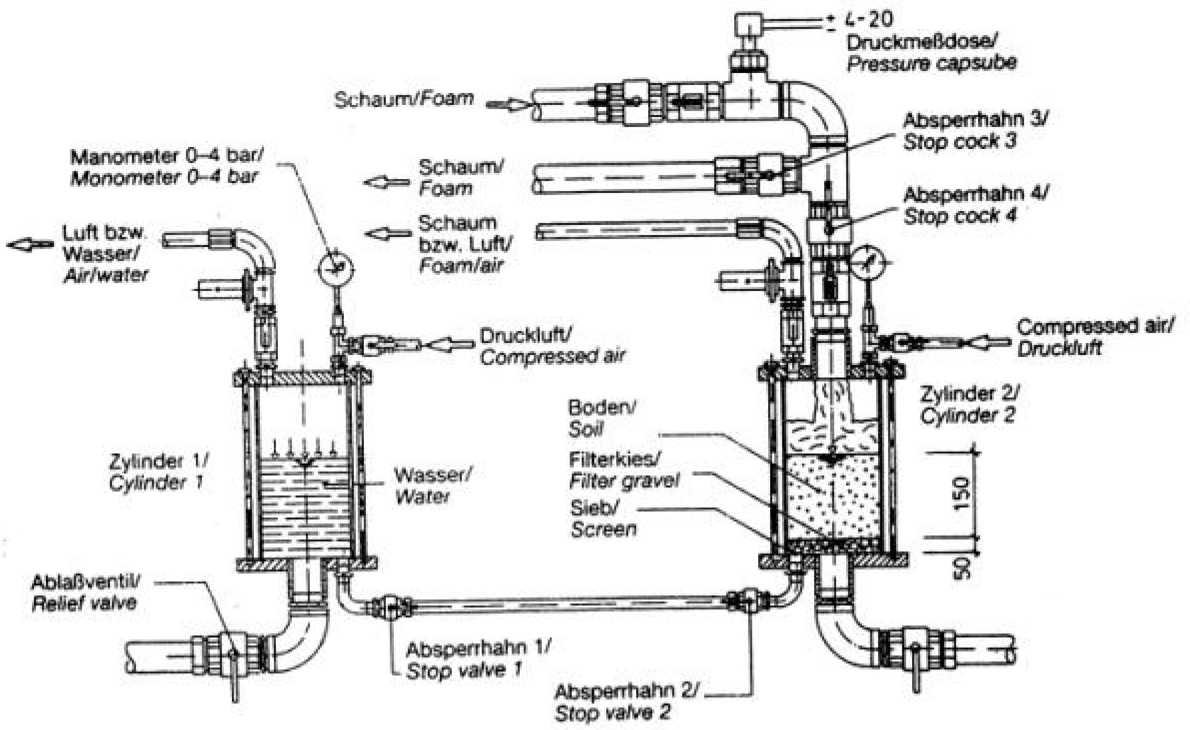


Figure 17 Apparatus for foam penetration test
[from Herrenknecht and Maidl (1995)]

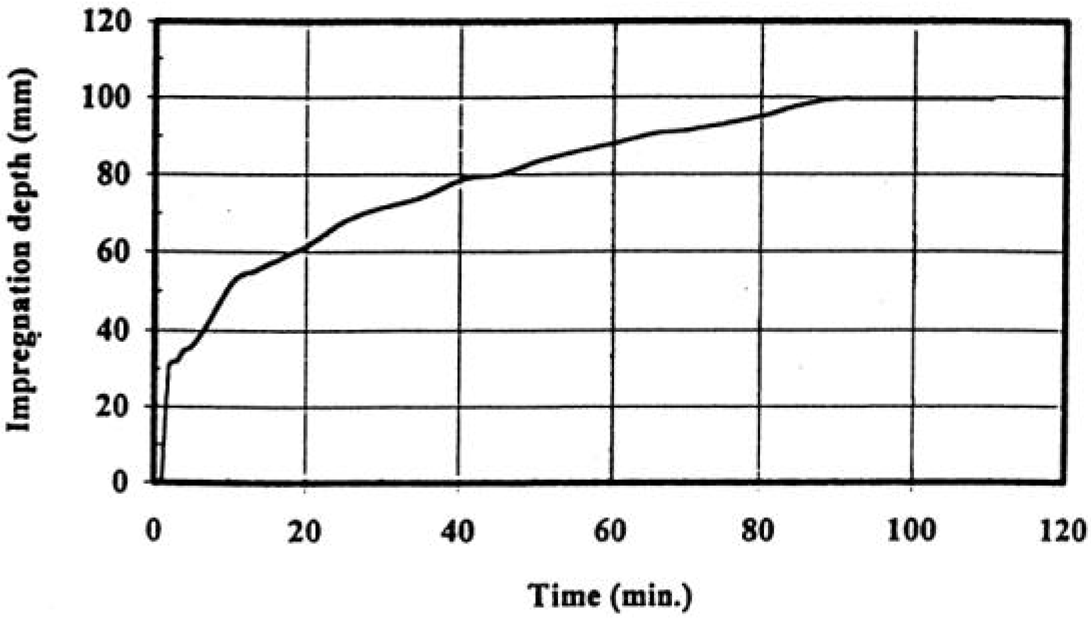


Figure 18 Result of a foam penetration test [from Quebaud et al. (1998)]

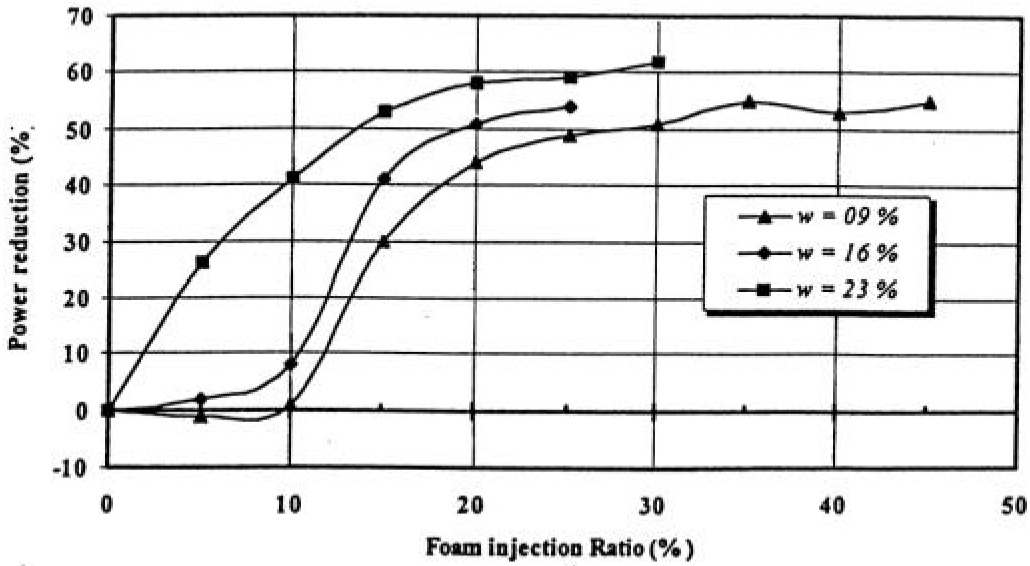


Figure 19 Power reduction in mixing soil due to addition of foam

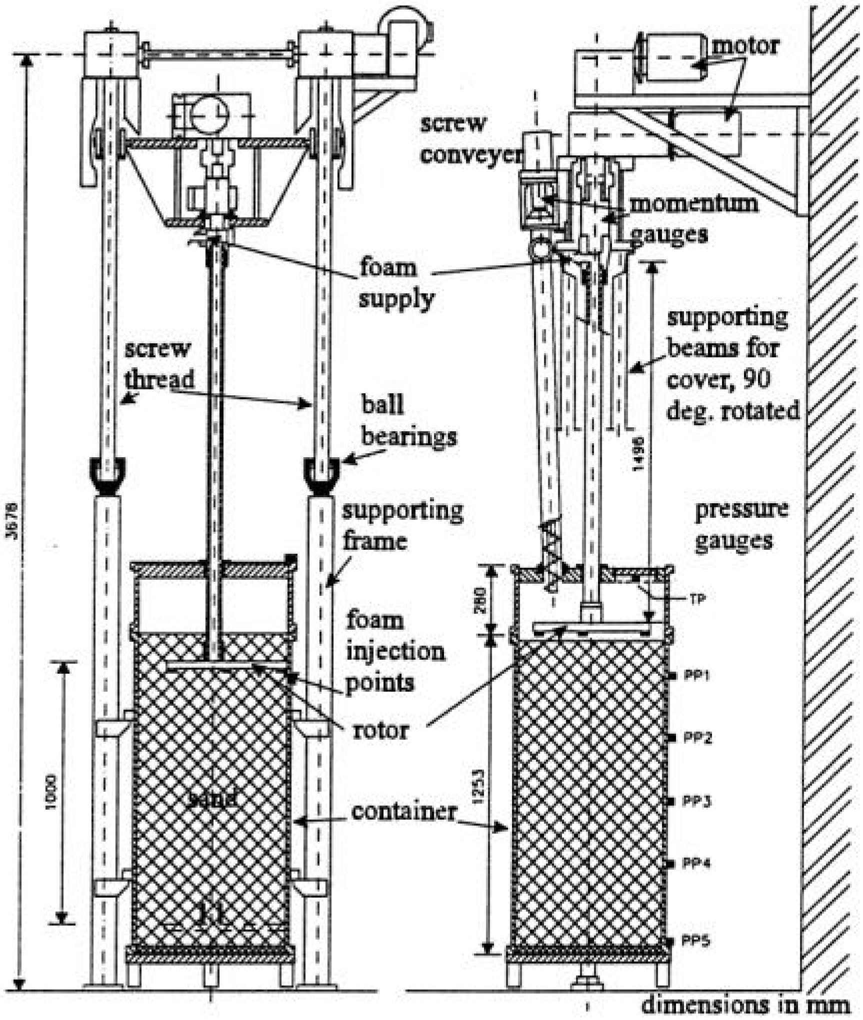


Figure 20 Apparatus for foam mixing and drilling tests [from Bezuijen et al. (1999)]