

Guide to **Support Fluids** for Deep Foundations

By the joint **EFFC/DFI** Support Fluids Task Group



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TERMINOLOGY	DEFINITION
apparent viscosity (AV)	The viscosity of a fluid measured at a given shear rate at a fixed temperature (the shear rate must be stated or defined). According to API 13B and ISO 10414-1, apparent viscosity (in mPa s or cP) is defined as one-half of the dial reading at 600 rpm (1022 sec ⁻¹ shear rate) using a direct-indicating, rotational viscometer.
barrette (LBE: load bearing element)	A barrette is a structural cast-in place diaphragm wall element, (with or without reinforcement), normally of I, H, L or T cross section in plan. Also referred to as a deep foundation.
bentonite	A material composed of clay minerals, predominantly montmorillonite with minor amounts of other smectite group minerals. It is commonly used in support fluids, either as pure bentonite suspension or in conjunction with polymers.
Bingham fluid model	A rheological model of a fluid with non-zero yield stress and a constant plastic viscosity.
bleeding	The separation of water from the solids in a fluid, principally due to gravitational settlement of the solids.
bored pile (drilled shaft or caisson)	Pile formed, with or without a steel casing, by excavating or boring a hole in the ground and filling with concrete (with or without reinforcement). Also referred to as a deep foundation.
clear spacing	Minimum space between individual reinforcement bars or bundles of bars, i.e. the opening for the concrete to flow through.
cover	Distance between the outside face of the reinforcement and the nearest concrete face i.e. the external face of the deep foundation element.
deep foundation	Foundation type which transfers structural loads through layers of weak ground into suitable bearing strata (piles and barrettes). In this Guide also refers to specialist retaining walls such as diaphragm walls and secant pile walls.
diaphragm wall	Wall comprising plain or reinforced concrete, normally consisting of a series of discrete abutting panels. In this Guide also referred to as a deep foundation.
dynamic viscosity	A property of support fluids that indicates their resistance to flow, defined as the ratio of shear stress to shear rate.
finer	In the support fluid, particles (as defined by the sand content test) less than or equal to 75 µm (US #200 mesh) in size.
filter cake	Formation of a cake of filtered material, such as bentonite and excavated soil from a suspension, built up in the transition zone to a permeable medium, by water drainage due to pressure differential.
filtration	The process of separating components of a support fluid by leaving the suspended solids as a filter cake on a filter medium (permeable ground) while the liquid passes through.
flowability	The ease of flow of fresh concrete when unconfined by formwork and/or reinforcement.
fresh concrete	Concrete which is fully mixed and is still in a condition that is capable of being placed by the tremie method. See tremie concrete.
gel strength	Peak shear stress measured at low shear rate ($\leq 5 \text{ s}^{-1}$ which is equivalent to the 3 rpm reading on a direct-indicating, rotational viscometer) after a support fluid has stood quiescent for a period of time.
hydromill	Diaphragm wall excavation equipment using two rotating wheels which remove cuttings by the reverse circulation technique. Also known as 'cutter' or 'hydrofraise'.
Interface layer (laitance layer)	Layer considered to accumulate between the support fluid and the concrete, possibly formed by material from segregated concrete and/or support fluid with soil particles.
Newtonian flow model	Model in which a linear relationship exists between shear stress and shear rate, where the coefficient of viscosity is the constant of proportionality.
Newtonian fluid	A fluid that follows the Newtonian flow model: $\tau = PV \cdot \dot{\gamma}$, where PV = plastic viscosity and $\dot{\gamma}$ = shear rate. Plastic viscosity is independent of the shear rate.
panel	Section of a diaphragm wall that is concreted as a single unit. It may be linear, T-shaped, L-shaped, or of other configuration.

Terms and Definitions / As used in this Guide

TERMINOLOGY	DEFINITION
plastic viscosity (PV)	<p>Plastic viscosity is the slope of a tangent to the shear stress rate plot at a specified shear rate.</p> <p>According to API 13B and ISO 10414-1, it is defined as the difference between the dial readings at 600 rpm and 300 rpm (1022 sec⁻¹ and 511 sec⁻¹ shear rate) using a direct-indicating, rotational viscometer and thus the API definition is the plastic viscosity over the shear range from 511 sec⁻¹ to 1,022 sec⁻¹ (measured in cP).</p>
polymer	<p>Materials formed of molecules from chained monomeric units. Natural polymers include natural gums, polysaccharides and biopolymers. Synthetic polymers include partially hydrolysed poly-acrylamides (PHPA) and cellulose modified polymer like polyanionic cellulose (PAC) Polymers may be used as the sole constituent of support fluids or as additives to enhance performance.</p>
rheology	<p>The science that studies the deformation and flow of matter. The term is also used to indicate the properties of a given fluid.</p>
shear	<p>The relative movement of parallel adjacent layers of fluid.</p>
shear rate	<p>The rate of change of velocity at which one layer of fluid passes over an adjacent layer.</p>
shear stress	<p>The shear force per unit area tending to induce fluid movement.</p>
sloughing	<p>The caving of soil or rock falling from the sidewall of the excavation. This term is not used to indicate a complete collapse of the excavation but rather shallow, near-surface caving that results in debris falling into excavation, and overbreak.</p>
sorption	<p>Sorption is a physical and chemical process by which one substance becomes attached to another. For the purposes of this document it is a process in which a species in solution moves from the fluid to a particulate solid. Thus cations (positively charged ions) may be sorbed onto negatively charged surfaces of clay minerals typically displacing other cations so that the process is an exchange (cation exchange). Polymers such as partially hydrolysed polyacrylamides (PHPAs) may be sorbed onto soil surfaces so reducing the active polymer concentration in the fluid. Sorption may be principally chemical (absorption) or physical (adsorption).</p>
specification	<p>Set of documents describing the requirements (in terms of performance or prescriptions) applicable for a particular project, product and/or work.</p>
specifier	<p>Person or body establishing the specification for the support fluid.</p>
support fluid	<p>Fluids and suspensions used in operations to support the sides of the excavation whilst drilling boreholes or digging trenches. May also carry cuttings in direct and reverse circulation operations.</p>
thixotropy	<p>The property of a material (fluid) that results in loss of fluidity (increase of viscosity or stiffening) when allowed to rest undisturbed or at constant shear rate, but which regains fluidity when shear stress is applied. Alternatively defined as a reversible time-dependent decrease in viscosity at constant shear rate. The viscosity of a thixotropic fluid changes with time under constant shear rate until reaching equilibrium.</p>
tremie concrete	<p>Concrete with the ability to achieve sufficient compaction by gravity when placed by tremie pipe in a deep foundation, under submerged conditions.</p>
tremie pipe / tremie	<p>Segmental pipe with waterproof joints to place concrete using the tremie method.</p>
tremie method (submerged concrete placement or slurry displacement method)	<p>Concrete placement method by use of a tremie pipe in order to prevent the concrete from segregation or contamination by the fluid inside the excavation, where the tremie pipe - after the initial placement - remains immersed in previously placed, workable concrete until the completion of the concreting process.</p>
volume yield	<p>The volume of fluid produced per weight of dry powder used.</p>
yield stress / yield point	<p>For an ideal Bingham fluid, gel strength and yield stress will be equal (yield stress of a real fluid is the intercept of the shear stress - shear rate plot on the shear stress axis).</p> <p>According to API 13B and ISO 10414-1, yield point (in Pa) is defined as: 0.48 (2x300 dial reading - 600 reading) using a direct-indicating, rotational viscometer (shear rate range from 511 sec⁻¹ to 1022 sec⁻¹).</p>

Abbreviations

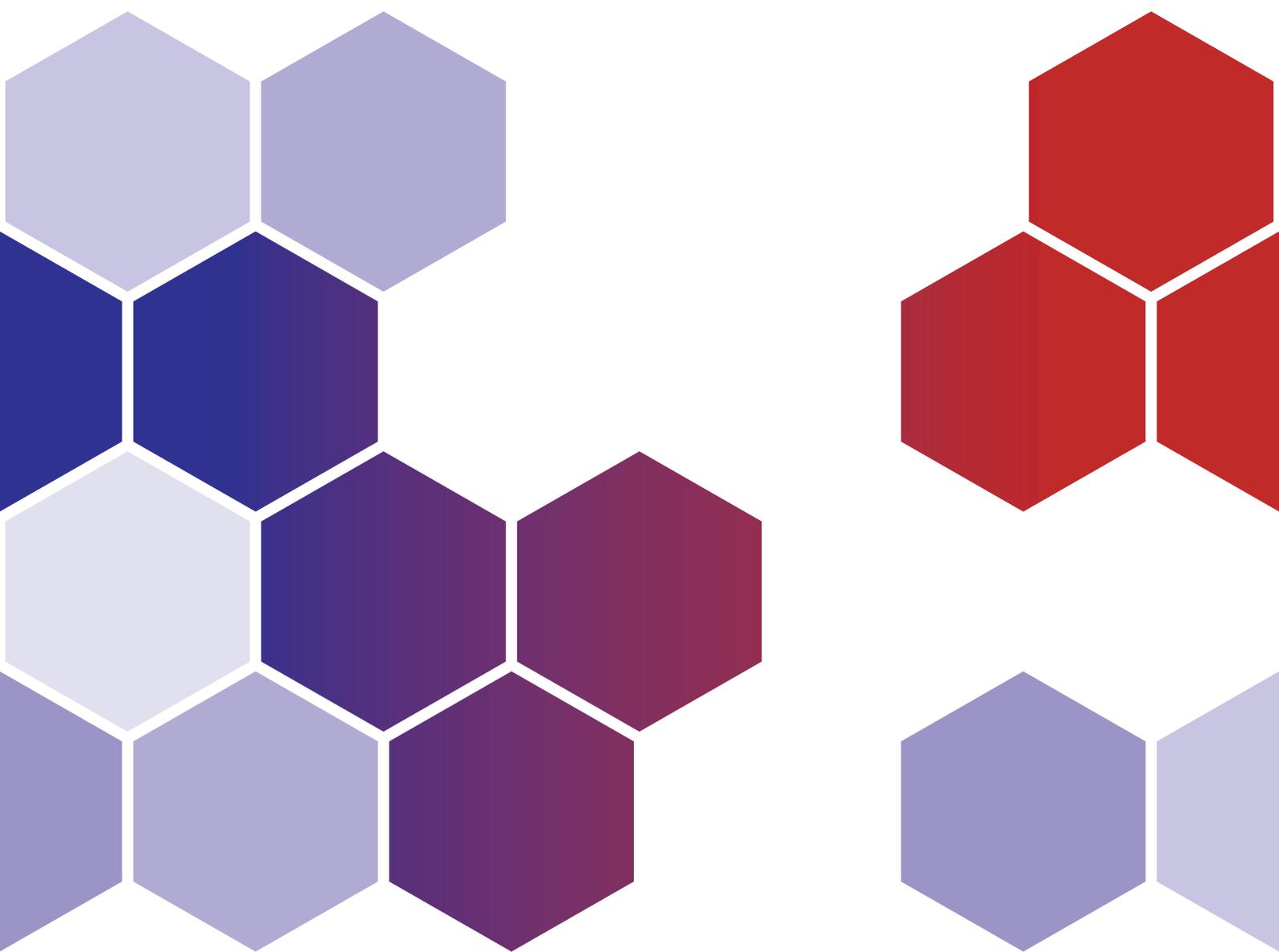
AASHTO	American Association of State and Highway Transportation Officials
ACI	American Concrete Institute
API	American Petroleum Institute
ASTM	American Society for Testing and Materials International
Caltrans	California Department of Transportation
CEN	European Committee for Standardization
CIRIA	Construction Industry Research and Information Association (UK organisation)
DAfStb	Deutscher Ausschuss für Stahlbeton (German Committee for Structural Concrete)
DFI	Deep Foundations Institute
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EFFC	European Federation of Foundation Contractors
FHWA	Federal Highway Administration
FPS	Federation of Piling Specialists (UK)
GEC	Geotechnical Engineering Circular (FHWA)
ICE	Institution of Civil Engineers (UK Professional Body)
ISO	International Organization for Standardization
QA/QC	Quality Assurance/Quality Control

Symbols

a	minimum clear spacing between reinforcement bars
c_{min}	minimum concrete cover according to structural or execution requirements
c_{nom}	nominal concrete cover = $c_{min} + \Delta c_{dev}$ (to be considered in design)
Δc_{dev}	allowance in design for construction tolerance
Δd_c	additional allowance in reinforcement cage design for installation
d_{b-t}	distance from bottom of excavation to tremie pipe outlet
D	dimension (diameter or thickness) of excavation or concrete element
D_{final}	diameter of the final spread of the concrete achieved in a slump flow test
D_{max}	maximum nominal upper aggregate size
D_{nom}	nominal excavation dimension, defined by excavation tool dimensions
D_s	reinforcement bar diameter
$D_{s,n}$	substitute diameter for a bundle of 'n' reinforcement bars
D_T	internal diameter of tremie pipe
h_1/h_2	embedment of tremie pipe before (h_1) and after (h_2) tremie pipe is cut
h_c	concrete level in excavation
$h_{c,T}$	concrete level in tremie pipe (= hydrostatic balance point)
h_F	fluid level in excavation
k	factor which takes into account the activity of a Type II addition
μ, μ_p	dynamic viscosity, plastic viscosity
$p_{i,T}$	hydrostatic pressure inside tremie pipe
p_o, p_i	hydrostatic pressure outside (p_o) and inside (p_i) the excavation
s_T	section length of tremie pipe section to cut
t_{final}	time for concrete to reach final spread in slump flow test
τ	shear stress
τ_o	yield stress
$\dot{\gamma}$	shear rate
γ_w	water density. γ is typically used for unit weight $\rho\gamma$ where ρ is density.

Section 1

General

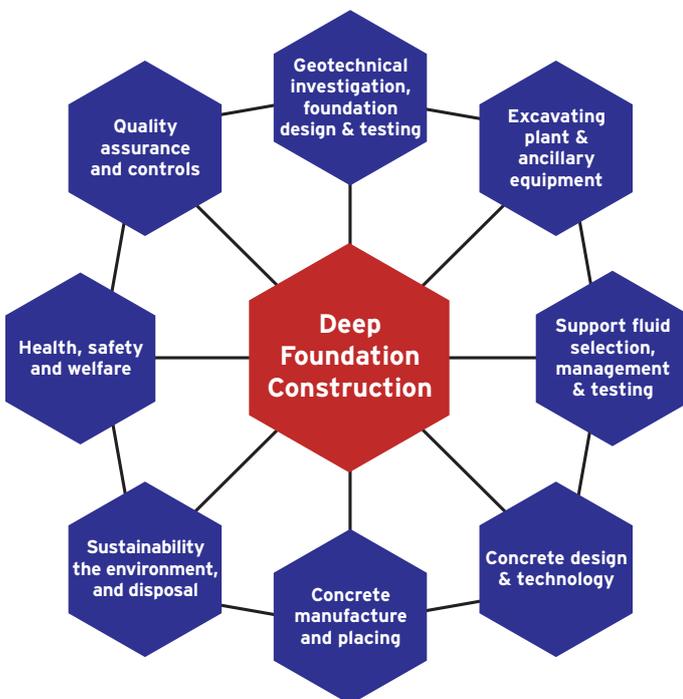


1.1 Introduction

'Support fluid' in Civil Engineering is a generic term used for materials that are manufactured and mixed with water to produce a compound that will support the sides of open and deep excavations for filling with tremie concrete. Support fluids are sometimes referred to as 'muds' and 'slurries' but this Guide only uses the term 'support fluid'.

Support fluids are an essential element in deep foundation construction, intrinsically linked to other parts of the construction process as shown in *Figure 1*.

FIGURE 1 DEEP FOUNDATION CONSTRUCTION ELEMENTS



Bentonite support fluids have been used since the sixties for the temporary support of excavations such as bored piles and diaphragm walls. Over this time the size and depth of foundation elements constructed using support fluids has increased significantly leading to increased excavation and concreting periods. In addition, there have been developments in excavation technology including hydromills so that rock materials can be excavated. Polymer support fluids have been developed more recently and have also been used successfully on a wide variety of projects. Successful use of all support fluids requires that their properties are fully understood and managed.

In Europe and North America, support fluids are normally based on bentonite clay, polymers (natural or synthetic) or a blend of

bentonite and polymer. Depending on the available raw materials and equipment, very specific properties can be achieved. These will change during the execution phases. Standards in Europe and North America require certain criteria for a support fluid to be met for use, re-use and for concreting. However, these Normative Standards may not be sufficient to allow consultants, designers and contractors to resolve the complex issue of controlling the fluid properties in order to not only reliably support an excavation but also to avoid materially affecting the concrete end product.

The key functions and requirements of a support fluid are:

- to maintain the stability of the excavation
- to flow easily as a liquid, with appropriate fluid properties
- to be readily displaced by concrete during concreting operations
- to retain their properties over time (should not react detrimentally with the soil physically or chemically)
- to manage the suspended particles
- to not react with concrete, considering both harm to the fluid and to the concrete
- to be economic (have a reasonable global price with regard to the base material as well as the production, control and disposal)

The technology for support fluids used in foundation works has largely evolved from experience in the Oil and Gas Industry where key requirements include ensuring the hole stability, allowing the best drilling rate to be achieved and removing the cuttings efficiently.

Fluency with support fluid properties is essential to ensure the quality of the completed works. This must include a sound technical understanding of the requirements for the whole process from site investigation, through excavation equipment, fluid preparation and usage, the usage of the excavated soil and the removal of used fluids.

The successful use of support fluids also requires a basic understanding of geotechnical principles and properties, training, on site experience and, crucially, documentation covering all the areas of use.

1.2 Background

In 2014, the EFC and DFI carried out a joint review of problems in bored piles (drilled shafts) and diaphragm walls cast using tremie methods. A Task Group was established and the 1st Edition of the "EFC/DFI Guide to Tremie Concrete for Deep Foundations" was published in 2016. The 2nd Edition was then published in 2018. Whilst the 1st Edition included recommendations on support fluid properties, it was clear to the Tremie Concrete Task Group that the preparation, characteristics and testing of support fluids required far greater discussion and review as the support fluid has a direct

impact on the quality and integrity of the final product in that the concrete and the support fluid are inextricably linked.

A Support Fluid Task Group was established in 2017 comprising Designers, Suppliers, Academics and Specialist Contractors, and this Guide is the output from the Task Group.

1.3 Purpose and Scope

To promote good practice in the use of support fluids for the construction of deep foundations, this Guide sets out the latest understanding of the behaviour of support fluids and also presents experiences drawn from recent research and case histories from around the world (Jefferis & Lam, 2013).

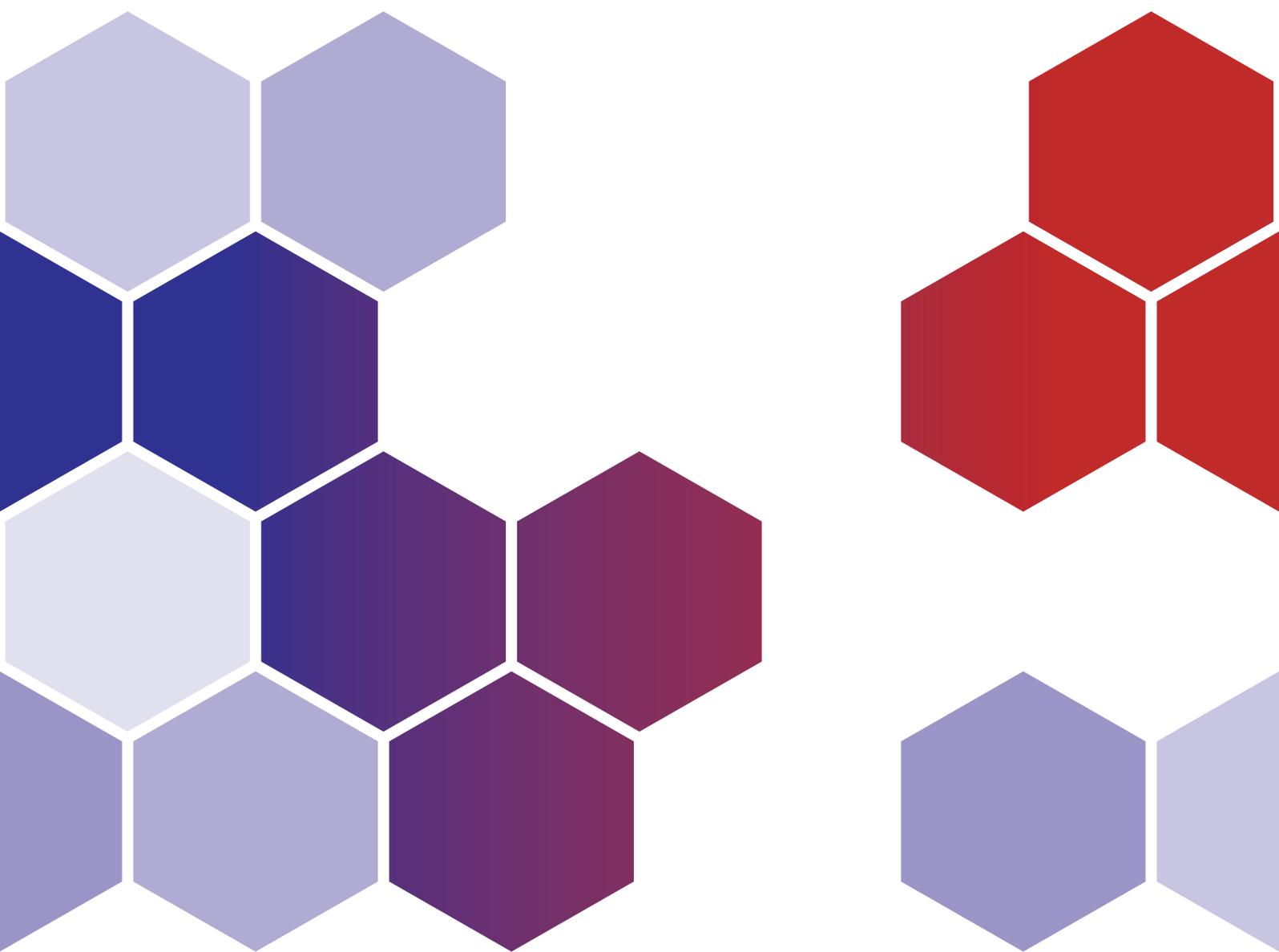
The purpose of this Guide is to present current understanding on bentonite, other clays, polymers and blended systems, including the advantages and limitations, in order to allow informed selection of the optimum technical solution(s) for the conditions on each individual worksite. This Guide does not recommend any particular type of support fluid as each worksite has specific characteristics and requirements.

This 1st Edition presents acceptance values for support fluids as given in commonly used Standards. With generous industry support, a detailed Field Research Study will commence in 2019 with visits to sites in both North America and Europe. Based on the findings of this study, it is hoped to give further detailed recommendations for management and control of bentonite, polymer and blended fluids and these will be contained in the 2nd Edition which is scheduled for publication in 2021/2022.

This Guide will assist individuals and corporations involved in the procurement, design, and construction of deep foundations including Owners/Clients, Designers, General Contractors, Academics and Specialist Contractors. It is intended as a practical addition to existing standards, not a substitute. Project Specifications, Standards and Codes should always take precedence.

Section 2

Design Considerations



2.1 Introduction

The effect of support fluids on the performance of deep foundation elements must be considered at the design stage. The type of support fluid can have a significant effect on both the geotechnical and the structural performance and this has to be considered at the start of the design process and allowed for and/or mitigated accordingly.

It is essential that high quality and rigorous construction methodology, specific to the support fluid being used, is developed and adhered to. This will minimize the effect of the support fluid on the performance of the foundation element in both the temporary and permanent condition, but will not eliminate all adverse effects and risks to the design.

2.2 Site Investigation

The selection and performance of the support fluid and the excavation equipment are dependent on the ground conditions. There are a range of support fluids available and the ground conditions will affect the final choice. The selection of excavation methods involving augers, buckets, grabs or reverse/direct circulation methods also depends on the ground conditions. In turn the type of excavation equipment affects the choice of support fluid.

To help this selection process it is essential that a suitably scoped contract site investigation is carried out to provide data at tender stage.

Table 1 sets out the deep foundation element construction stages and the main effects that the ground has on the support fluid. The key soil/rock properties are also listed for these stages. These main effects are discussed in detail in different sections of the guide and the relevant sections are listed in Table 1.

TABLE 1 SITE INVESTIGATION INFORMATION NEEDED TO ASSIST WITH SUPPORT FLUID SELECTION

Construction Stage	Soil/rock properties required from the site investigation	Interactions	Guide Section
Environmental impacts.	Permeability and jointing.	Groundwater may be used for drinking water and could be affected by the support fluids.	4.4
	Watertable levels, flow rates, artesian conditions, etc.		
Support Fluid Mixing.	Ground water chemistry. Local water supply chemistry.	Mixing water chemistry can change the support fluid properties.	4.6
Excavation.	Soil and groundwater characteristics, including utilities.	Guide wall and working platform stability.	-
	Soil/rock classification and mechanical properties.	Affects selection of digging equipment.	5.3
	Soil/rock permeability (including cavities and karsts).	Affects fluid loss and trench stability.	2.4
		Affects filter cake thickness and shaft resistance.	2.5
	Soil/rock type.	Fine grained soils and rocks remain in suspension.	5.4
	Ground water chemistry (e.g. contamination)	During excavation the groundwater and soil particles can mix with the support fluid, which can change the support fluid properties.	5.4
	Soft and weak soils such as peat and alluvium.	Localised areas of instability may require pretreatment.	-
Base cleaning.	The properties of the end bearing stratum affect the cleaning tools.	The design requirements for pile end bearing affects the base cleaning.	5.3
Concreting.	Base debris. Interface layer.	Base debris contributes to the interface layer and inclusions.	5.6
Recycling and desanding the support fluid.	Soil grading.	Silts and clays are hard to remove from contaminated mineral support fluids.	5.5
Disposal.	Soil grading.	Support fluids contaminated with clay are harder to clean and have to be disposed of in larger quantities.	5.7

Note: Site investigation may be best served by using two different drilling/sampling methods in order to identify the entire soil column; this benefits both the design engineer and the contractor tendering. Boring logs showing blanks and poor recovery lead to questions marks and increased risks. CPT, sonic sampling and instrumented blind drilling can complement basic split spoon sampling and SPT's. Incidents occurring during the site investigation works such as fluid loss or unusual casing advancement must be reported on the boring logs.

Annex B.3 of EN 1997-2 and FHWA GEC #10 give detailed recommendations for the required scope of Site Investigations.

2.3 Support Fluid Functions

The fundamental purpose of a support fluid is to maintain stability of the excavation throughout the excavation process and until the support fluid has been replaced by concrete. For some types of excavating equipment such as a hydromill the fluid has an additional role to carry the cuttings from the hydromill head to the separation plant.

The hydrostatic pressure head of fluid within the excavation is critical to ensure stability by providing a stabilizing pressure at the face of the excavation and by counteracting the destabilizing head pressure of the groundwater in the soil around the excavation. To be effective, the stabilizing pressure must act at the fluid-soil interface or within a very short distance (in the order of a few cm or inches) into the soil. If the fluid pressure does not act at or close to the soil face, there is a risk of progressive sloughing of soil at the face.

Fluids can include water or water mixed with additives such as minerals (bentonite) or polymer. The additives are used to help contain the fluids within the hole and minimize fluid loss through seepage out through the face of the excavation, thereby allowing the positive head pressure to be maintained. Water mixed with additives to alter the fluid properties is often referred to as “slurry” or “mud” and the construction technique is sometimes referred to as “slurry drilling” or “fluid supported excavation”.

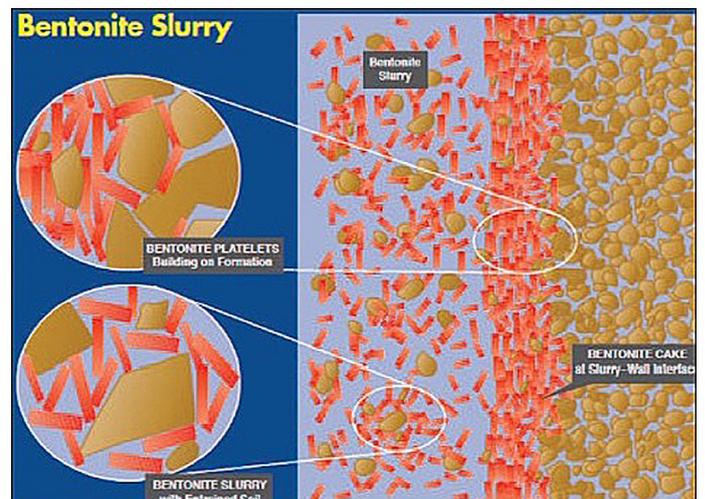
Plain water can provide a stabilizing influence if the water head can be maintained within the excavation (see *Section 4.7*). Water can also function as a drilling fluid to convey drill cuttings as for example with reverse circulation drill tools. A major limitation exists with plain water as a support fluid because the fluid escapes quickly into permeable soils and therefore the net positive pressure inside the excavation is lost and the water pressure within the adjacent soil increases. The effective pressure in the adjacent soil becomes very small. This leads to sloughing of non-cohesive soil at the face of the excavation. Water is therefore only suitable as a means of counteracting groundwater for excavations within cohesive or cemented soils or rocks that are inherently stable without a stabilizing pressure within the excavation or for cased excavations.

Bentonite Fluids

Bentonite clay is the most commonly used mineral additive for support fluid, with a long history of use in oilfield drilling applications. Bentonite is a clay composed primarily of montmorillonite clay minerals which can absorb water to many times their own weight. When added to water, relatively small amounts of bentonite form a colloidal mixture with the effect of increasing the viscosity of the fluid over that of water, along with a small increase in unit

weight. Besides the viscosity and unit weight, bentonite has the beneficial property of forming a filter cake on the face of the excavation which acts to restrict fluid loss into the surrounding soil and allow a positive hydrostatic head to be maintained within the excavation. The filter cake forms as the bentonite particles are filtered out of the fluid as the hydrostatic head within the excavation drives the fluid into the surrounding permeable soil.

FIGURE 2 SURFACE AND DEEP FILTRATION



This filter cake will consist of bentonite and excavated soil. Filter cake formation can be expected to be effective in sealing fine to medium grained soils with relatively little penetration of bulk fluid into the soil. The filter cake characteristics are influenced by the amount of native clays, silt, and sand that is present in the support fluid. High solids contents can lead to thick filter cakes. Filter cakes do not normally form on low permeability soils such as clay.

In more open soils such as coarse sands, gravels or fissured grounds the support fluid penetrates into the soil until it comes to a standstill as a result of clogging of the soil with solids in the support fluid (bentonite and excavated soil suspended in the fluid) and gelling of the support fluid. A filter cake then forms on the clogged soil to form an interface between the fluid in the excavation and the surrounding soil. Sand may be added to the support fluid to promote clogging by deep filtration. (Hutchison et al 1963)

Besides the filter cake formation, rheological blocking provides another mechanism to restrict fluid loss in more open soils and those with fissures, for example, in chalk. Rheological blocking is the process whereby the support fluid continues to penetrate until its gel strength acting over the fluid wetted soil can restrain the differential pressure between support fluid and the external groundwater.

In open soils or fissures, penetration distances can be substantial unless, as usually happens, sealing is helped by mechanical blocking by solids in the support fluid (surface and deep filtration). With rheological blocking, the support pressure initially acts some distance into the soil, until over time a filter cake develops at the excavation face formed by the penetrated fluid. The penetrated fluid will have some permeability.

Polymer Fluids

Polymers are increasingly used as support fluids in construction worldwide, and these materials present different behaviour compared to bentonite support fluid. The polymers are often synthetic long chain or high molecular weight (typically partially hydrolysed polyacrylamides, or PHPAs) though as presented in this Guide, other types of polymers can be used. Within the polymer types, different performance requirements can also be accepted.

High molecular weight synthetic polymers

Synthetic polymers are long chain-like hydrocarbon molecules, which interact with each other, with the soil and with the water to effectively increase the viscosity of the fluid. The appearance of the polymer fluid is that of a slippery, slimy viscous liquid. A scanning electron micro-photograph of a polymer fluid magnified to 800 times its actual size is shown in *Figure 3a*.

The support fluid function then relies on a combination of factors:

- viscosity of the polymer to control the flow rate into the formation
- ability to form a membrane at the face of the excavation
- pore blocking and surface filtration of the solids put into suspension during the drilling operation

The main process limiting fluid loss and maintaining hydrostatic pressure is the viscosity of the polymer fluid and the viscous drag. Polymeric strands tend to form a three dimensional lattice structure assimilated as a membrane (*Figure 3b*) Viscosity and viscous drag will significantly reduce the effective conductivity of the permeable soil by polymer. However, some fluid loss into the surrounding soil is inevitable and fluids may need to be added throughout the duration of the works until concreting to maintain the excess hydrostatic head that provides support and stability.

Although some polymer support fluids can form a membrane, at the soil face, with pure PHPAs the formation of a filter cake at the face of excavation tends to be more limited than with bentonite fluids as PHPA fluids are operated at much lower suspended solids contents than bentonite fluids (the bentonite clay contributes to the solids content of a bentonite fluid). PHPA fluid viscosity also

limits penetration. Whilst thin, the cake that does form may be effective in sealing the excavation face with a similar mechanism as exists with bentonite support fluid. The thin cakes characteristic of PHPA fluids appear to provide benefit in terms of shaft resistance..

The long polymer chains can be damaged by pumping (see *Section 5* and *Appendix C*).

Natural Modified Polymers

Natural modified polymers such as modified celluloses (e.g. polyanionic cellulose, PAC) have been successfully used in the reverse circulation process (e.g. hydromill), especially where challenging chemically aggressive ground conditions are encountered. Though pure polymer mixes with PAC were used, the specification on the fluid remained driven by the excavation process and acceptance values applied for bentonite can be used with success. In such systems, PAC is less sensitive to soil and water chemistry, and the resulting soil/polymer system allows a thin controlled filter cake to be formed which participates in the stabilization process.

Natural modified polymer chains are normally not damaged by pumping operations.

FIGURE 3.A SCANNING ELECTRON MICRO-PHOTOGRAPH OF POLYMER DRILLING FLUID (photo: Univ. of Missouri-Columbia)

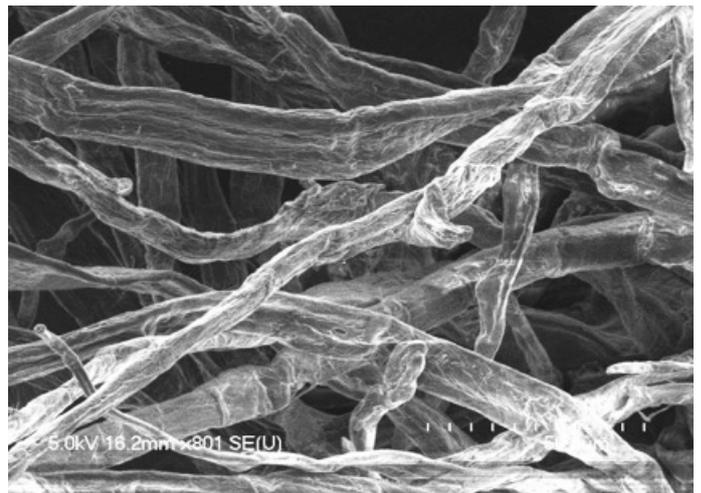


FIGURE 3.B SYNTHETIC POLYMERS USED IN SUPPORT FLUIDS



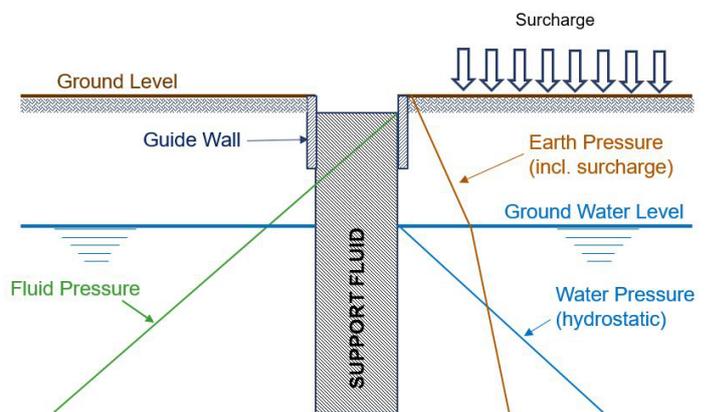
groundwater level can provide a stabilizing effect. If, however, the soil has high permeability water will typically flow out into the surrounding soil so that the stabilizing excess head is lost. The addition of bentonite or polymer admixtures to water facilitates the maintenance of a stabilizing head by controlling fluid loss from the excavation into the formation as described in *Section 2.3*.

Any flow of groundwater into the excavation will exert a destabilizing effect which can cause collapse and careful maintenance of the fluid head and quality is essential to minimise this risk. Soils with significant cohesion (clays or cemented soils) may appear to be inherently stable but the inflow of groundwater through granular or weakly cemented layers may result in loss of stability unless suitable support fluids are used.

In planning the construction process to maintain a stabilizing fluid head pressure it is critical that the groundwater head in the surrounding soil is known with confidence. Sometimes different strata may contain groundwater heads at different levels due to artesian conditions or perched watertables - each condition within the profile represents a situation for which the support fluid must provide a stabilizing head pressure within the excavation.

If the support fluid is contained within the excavation with an effective membrane at the excavation sidewall and/or with minimal penetration into the surrounding soil, then the full hydrostatic pressure acts on the face as illustrated in *Figure 4*. Bentonite fluid forms a membrane by the filter cake at the excavation face. With polymer fluid, the membrane can effectively be formed if the fluid properties are sufficient to produce a high seepage gradient over a short distance close to the excavation face, or when the support fluid encapsulates soil fines creating a thin filter cake.

FIGURE 4 HYDRAULIC SUPPORT WITH FULL MEMBRANE EFFECT (SCHEMATIC ONLY - NOT TO SCALE)



2.4 Temporary Stability

The basic principle of a support fluid to provide excavation stability is that the fluid must provide a net pressure within the excavation which is always greater than the sum of the earth pressure and horizontal pressure due to surcharge in the surrounding soil. The net fluid pressure is the difference between the fluid pressure within the excavation and the external groundwater pressure.

This net fluid pressure provides a stabilizing effect to the face of the excavation. A net pressure of plain water above the

If there is insufficient membrane or high fluid loss, the support fluid will penetrate into the formation. In this case only a part of the supporting force is transferred within the relevant failure body and the *effective* supporting force will be reduced significantly. In the extreme case fluid penetration into the surrounding soil occur may extend beyond the theoretical failure body of soils.

Neither a perfect membrane nor a maximum penetration governed only by rheological properties is observed. For coarse grained soils or gravels with high permeability, particles suspended in the support fluid due to excavation operations or added intentionally to assist pore blocking can often form a filter cake inside the formation. This results in reduced penetration rates and shifts the support forces closer to the excavation wall. A fuller discussion on the issues described above is given in *Appendix A*.

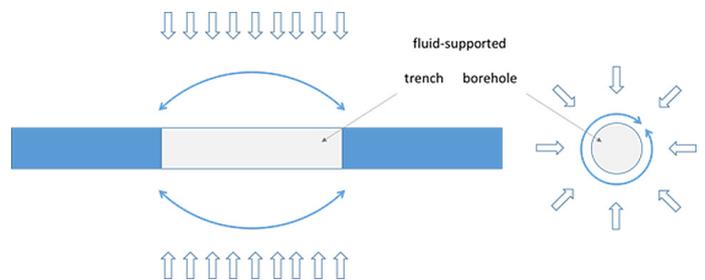
A range of calculation methods has been developed that attempt to assess the theoretical destabilising pressures exerted by the surrounding ground on a fluid filled excavation. Such calculation methods are useful but should be used with caution and are no substitute for relevant experience and some basic rules. In typical construction conditions, an excess hydrostatic pressure provided by 2 m to 3 m [7 ft to 10 ft] of support fluid head is usually sufficient to maintain stability during excavation. The ICE SPERWALL recommends a minimum 2 m [7 ft] excess head (the difference between the fluid level and the groundwater level).

Arching Effect

Soil arching effect plays an important role in transferring stress around the open excavation so that the lateral stress provided by the support fluid is predominantly required to prevent localized collapse in the soil close to the excavation opening. This is only relevant for relatively short excavation lengths, but within the length of most diaphragm wall panels.

Arching is an important concept for understanding excavation stability, and how the techniques described above can be effectively employed in construction. When a circular vertical hole or a rectangular diaphragm wall panel is excavated in soil, arching allows the in-situ lateral stresses in the ground to be transferred around the opening so that the opening can be maintained (*Figure 5*). Even with the use of casing or drilling fluids for support, the majority of the lateral stresses in the ground must transfer around the hole.

FIGURE 5 ARCHING EFFECT ON A RECTANGULAR PANEL AND A CIRCULAR VERTICAL HOLE



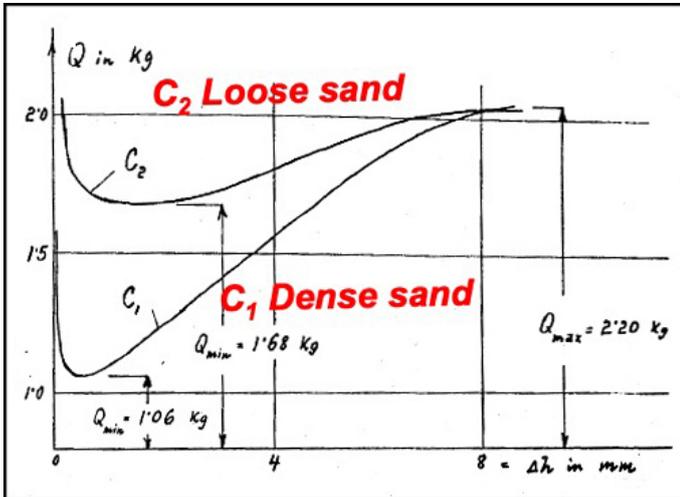
As the excavation is advanced, the soil around the hole moves inward slightly, thereby allowing lateral stress to be transferred via arching around the hole as shown on the right in *Figure 5*. This transfer of radial stress to tangential stress around the hole allows a small amount of fluid pressure or casing support to stabilize the excavation.

This effect was demonstrated in the famous “trap-door experiment” described by Terzaghi⁽¹⁹³⁶⁾, in which he measured the force required to support a trap door in the bottom of a sand-filled box. His measurements demonstrated that the force required to support the trap door diminished as the door was slightly opened as a result of interlocking soil particles acting to redistribute the stress around the door. The force was observed to diminish to a much smaller magnitude for dense sand than for loose sand (*Figure 6*), an effect that was recognized as the more effective arching in the stronger soil. As the door progressively opened further, the arching collapsed and the force on the door returned to levels near the original values.

Similar principles are at work during excavation of a bored pile (drilled shaft) or diaphragm wall panel. The stabilizing radial stress provided by 3 m [10ft] of fluid head pressure is relatively low (about 30 kPa or 4 psi) compared to in-situ lateral earth pressures, but is observed to be effective at maintaining stability because this stress is typically sufficient to support the soil to the point of maintaining the arching effect^(Washbourne 1985).

Experienced constructors know that denser soil is more easily stabilized than loose soils, and the reason for this observation is partly explained by arching. Looser soils will also require greater inward displacement to develop arching. A small diameter hole is more forgiving than a larger diameter hole, because arching is more easily accomplished. For the same reasons, piles are less problematic than diaphragm wall trenches. As Terzaghi’s trap door experiment demonstrates, if the radial support is insufficient or too much inward movement occurs, collapse of the soil can occur.

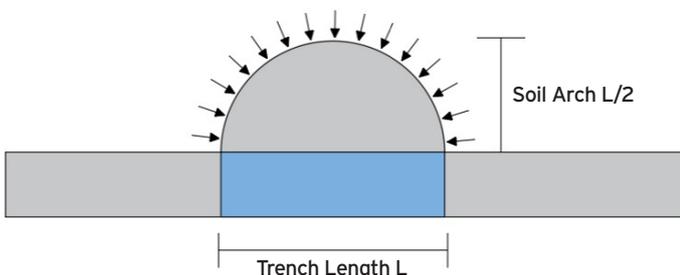
FIGURE 6 EFFECT OF SOIL TYPE ON THE EXCAVATION STABILIZATION (TERZAGHI, 1936)



where Q = force required to restrain trap door (originally reported in kg force)
 Δh = opening displacement of trap door (mm)

The stability of the fluid filled trench can be assessed using the method described by Davies et al ⁽¹⁹⁸⁰⁾ following the principles adopted in Huder, J. ⁽¹⁹⁷²⁾. The method assumes that the soil can create a stable arch around the trench opening, with only the half-cylinder of soil within the arch exerting a pressure onto the support fluid in the trench. Terzaghi's silo theory is used to calculate residual forces from the half-cylinder that need to be resisted by the support fluid allowing for vertical shear development around the perimeter of the arch. The model considered is shown in Figure 7.

FIGURE 7 SOIL ARCH ADJACENT TO THE PANEL



Stability of the Final Element in Closed Systems

Where an excavation is made through permeable strata in a closed system (e.g. access shaft) it is likely that a pumping well within the shaft will be necessary to relieve piezometric pressure and retain the stability of the closing panel excavation to be carried out, during its construction. Where such soils are saturated only a small flow of

filtrate from the fluid into the soil will cause a rise of pore pressure in the soil. This increase will occur more readily where the permeable stratum is capped above and below by impermeable layers. Relief of any excess pore pressure by pumping ensures an adequate differential head of support fluid and allows the closing panel excavation to be carried out in stable conditions. ^(Puller, 2003)

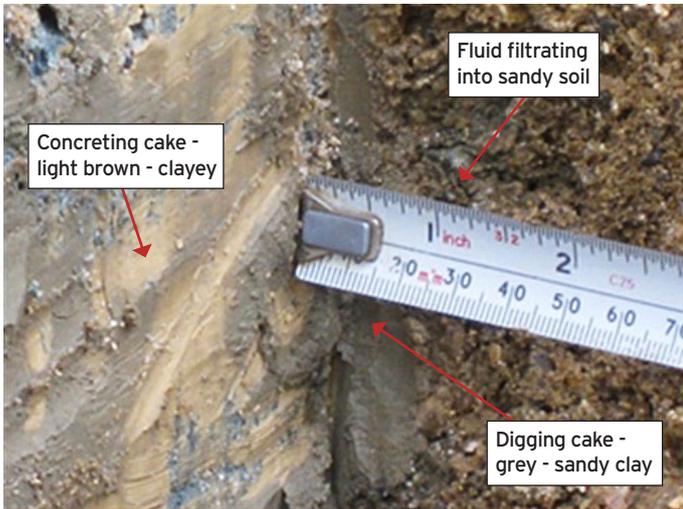
2.5 Shaft Resistance and Base Resistance

There is no specific guidance in European or North American standards that recommends how to take account of the potential effect of the support fluid on the geotechnical capacity of piles and diaphragm walls, but it is essential that this is considered as part of the design process. A full scale trial can be used for the capacity assessment, as discussed in Section 6. In any trials, the fluid properties, method of construction, and the time the excavation is open should mirror those to be used in the main works e.g. trial excavation should be with used support fluid.

With piles and/or barrettes, it is good practice to carry out full scale pile load tests to check the actual capacity of the piles. It is normally not possible to carry out load tests on diaphragm walls. Where full scale tests are carried out, it is essential that suitable methods and control parameters are used and documented for the tests, and that these methods are maintained throughout construction of the deep foundation elements to ensure the validity of the tests.

The effect of bentonite on the shaft resistance and base resistance of piles and diaphragm walls is reasonably well known ^(Fleming and Sliwinski 1991). Figure 8 shows an example of a filter cake. The thin light brown section of the filter cake on the face of the concrete panel was formed prior to concreting when the support fluid solids content was low and the cake it produced was of low permeability. The thicker grey filter cake formed during the excavation process when the cake permeability and fluid solids content were higher. This filter cake was formed during a diaphragm wall panel excavated using a grab. Similar cakes have been formed with the hydromill. The fluid from the bentonite slurry can be seen to have infiltrated into the adjacent sandy soil. The effect of polymer fluids on shaft and base resistance is becoming better understood, and early research suggests that, in permeable soils, the adverse effects on shaft resistance are less severe than when using bentonite ^(Lam et al, 2010).

FIGURE 8 PHOTOGRAPH OF BENTONITE CAKE FROM DIAPHRAGM WALL PANEL, SHOWING A 1MM [0.04 IN] CLAYEY, LIGHT BROWN, CONCRETING CAKE AND A 19 MM [0.75 IN] GREY SAND CLAY EXCAVATION CAKE



The EFFC/DFI Tremie Concrete Guide contains a detailed discussion on structural design issues in *Section 2* and *Appendix E*.

Adequate base cleaning is essential to ensure good base resistance, regardless of whether mineral or polymer support fluids are used. The end bearing capacity of piles and diaphragm wall panels can be affected by the presence of debris and support fluid left behind as part of the construction process. Appropriate levels of base cleanliness should be discussed and agreed at the project design stage and verified accordingly on site. A range of methods for checking base cleanliness is available and some examples are provided in FHWA #10 and in ICE SPERWALL. Further detail is given in *Section 6.2* of the EFFC/DFI Tremie Concrete Guide.

2.6 Structural Design

In the structural design of piles and diaphragm walls constructed under support fluid, the potential for an effect on the bond between the reinforcement and the concrete due to the use of the support fluid should be considered.

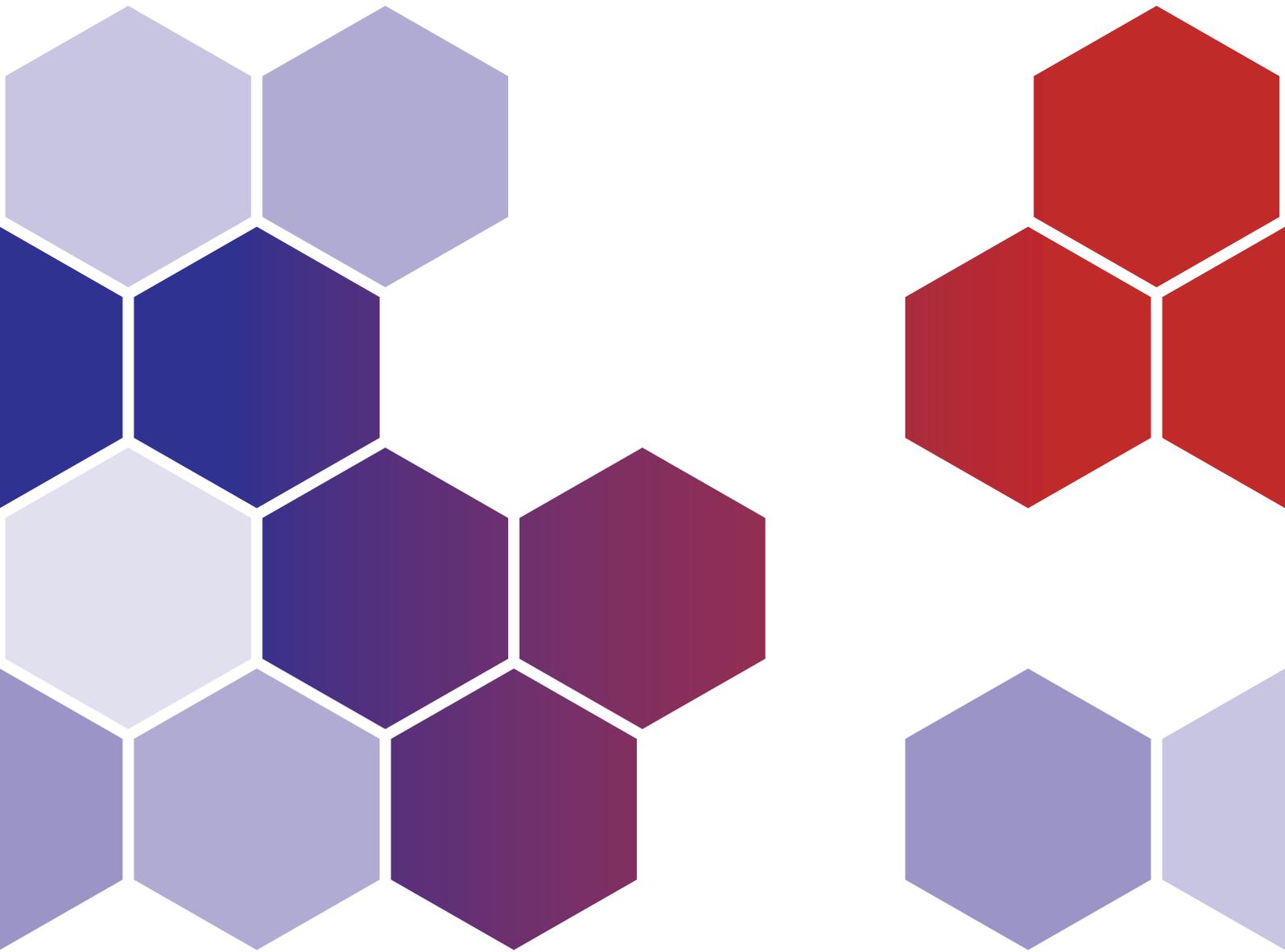
(Jones, 2004; Jones, 2005; Bowen, 2014; Costello, 2018; Costello et al., 2019)

The area of design relating to support fluid is covered tentatively in EN 1992-1 where Section 8.4.2 recommends using factored bond capacity based on 'quality of bond condition'.

It is essential that reinforcement congestion be minimized as this is a main contributor to poor concrete flow through the reinforcing cage. The minimum reinforcement bar spacing and maximum rebar density should be strictly maintained in accordance with applicable Standards (e.g. EN 1536, EN 1538, ACI 318 and ACI 336).

Section 3

Properties of Support Fluids



Support fluid properties are characterized by a series of tests that are used both for fluid management during the execution of the work and as a Quality Control protocol.

The order of importance and emphasis will vary according to the type of support fluid considered. Three different classes of support fluid (see Section 4) require a separate analysis of their properties and subsequent range of values to be attached to them. The three classes are:

- mineral (e.g. bentonite)
- natural (e.g. gum), and modified natural polymer (e.g. CMC and PAC) used alone or blended with bentonite
- synthetic polymer (e.g. PHPA) - usually used alone

3.1 Rheology

Rheology is the study of the deformation and the flow of materials under the effect of applied stresses. The rheology of support fluids influences many aspects of their behaviour including:

- pumping the fluid to and from the excavation
- surge pressures in an excavation as a tool is raised and lowered
- draining of the fluid from the tool as it is raised from the excavation
- penetration of the support fluid into the adjacent soil
- sedimentation of excavated soil in the support fluid
- displacement of the support fluid from reinforcing bars and the walls of the excavation by rising concrete during concreting
- removal of soil at the separation plant

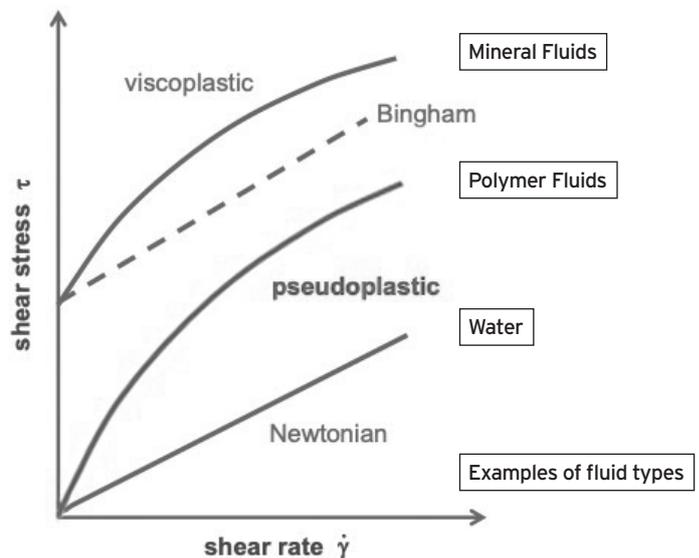
Fluid rheology can have secondary impacts including:

- filter cake thickness and possible detrimental effects on shaft resistance
- excavation stability
- disposal of unwanted fluid on completion of the works

The flow behaviour of support fluids can be investigated by plotting shear stress as a function of shear rate. Figure 9 shows shear stress - shear rate plots for some idealised flow types with examples of fluids that may show these rheologies.

As per standard practice, the Apparent Viscosity, Plastic Viscosity and Yield Stress values are measured and provided according to ISO 10414-1:2008, Part 1, using a two speed rheometer, at 300 and 600 rpm.

FIGURE 9 FLUID RHEOLOGIES



Rheological Models

It is useful to develop models to fit rheological data such as the profiles shown in Figure 9. Some basic models are considered in the following sections working from the most basic to the more complex.

Newtonian Fluids

The flow behaviour of Newtonian fluids in laminar flow can be described by a simple one parameter model:

$$\tau = \mu \dot{\gamma}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate and μ is the viscosity of the fluid.

Water and mineral oils are examples of Newtonian fluids.

Bingham Fluids

Some fluids show both liquid and solid-like behaviours. The most basic model for such fluids is the Bingham model:

$$\tau = \tau_0 + \mu_p \dot{\gamma}$$

where τ_0 is the yield stress and μ_p is the plastic viscosity.

The Bingham model is commonly used to describe bentonite fluids though these actually show more complex flow behaviour including time dependent effects as described below.

Power Law Model

For some fluids, including solutions of many polymers, the shear stress-shear rate relationship can be described by a power law model:

$$\tau = m\dot{\gamma}^n$$

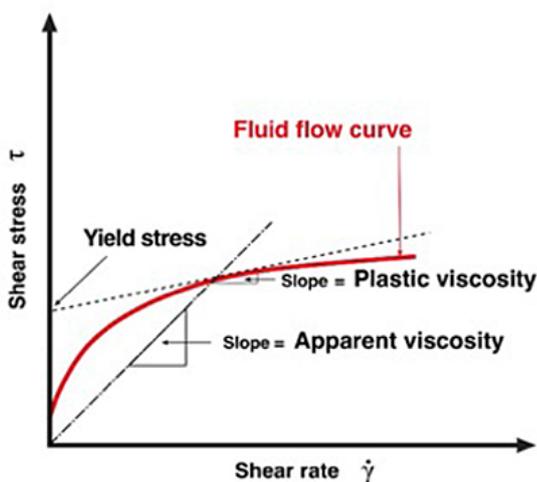
where m and n are two curve fitting parameters. m is known as the fluid consistency coefficient and the flow behaviour index.

For a Newtonian fluid, $n = 1$ and m becomes the viscosity. For pseudoplastic polymer solutions n is less than 1. As a detail, $n > 1$ gives a shear thickening behaviour.

Because of the convex curvature of the shear stress-shear rate plot for power law fluids with $n < 1$, they have an apparent yield stress - at any finite shear rate, a tangent to the plot will not pass through the origin (see Figure 10). Hence they are known as pseudoplastic fluids. Typically, data for PHPA solutions can be fitted to a power law model though the model is not appropriate for very low or very high shear rates. At very low shear rates where molecular interactions are not disturbed by flow, the fluid viscosity tends to a constant value. At very high shear rates where shearing dominates molecular interactions, the solution viscosity tends towards that of the solvent (water for PHPA support fluids). The difference in viscosity between very low and very high shear rates can be very substantial from a few hundred to over one million.

Figure 10 shows the yield stress and plastic viscosity for a generalised rheological flow curve of non-Newtonian fluids.

FIGURE 10 RHEOLOGICAL PARAMETERS FOR A GENERALISED NON-NEWTONIAN FLUID



From Figure 10:

- Plastic viscosity is the slope of a tangent to the shear stress-shear rate plot at any given shear rate. For mineral fluids, polymer fluids and non-Newtonian fluids in general, this slope will be a function of shear rate and thus the shear rate should be stated when citing plastic viscosity values.
- Yield stress is the intercept on the shear stress axis of the tangent to the shear stress - shear rate plot. As for plastic viscosity, the modelled yield stress, will be shear rate dependent.
- Apparent viscosity is the viscosity obtained if the fluid is assumed to be Newtonian. It is therefore the slope of a line from the origin to the shear stress-shear rate plot. With the exception of Newtonian fluids, apparent viscosity will vary with shear rate and thus the shear rate should be stated when citing apparent viscosity values.
- Just as the apparent viscosity is the viscosity obtained by assuming a fluid is Newtonian, apparent viscosity, μ_p and the yield stress, τ_0 are the Bingham model parameters if the fluid is assumed to follow the Bingham model.

Time Dependent Effects

Some fluids show a change in rheological properties with time, as a trite example, over time fresh concrete transforms from a semi fluid to a solid. Bentonite support fluids can show stiffening with time. However, the effect is reversible, gel will re-build when the fluid is left quiescent but fluidity is restored on shearing. This effect is known as thixotropy.

Thixotropic effects for bentonite support fluids can be demonstrated by measuring the gel strength. For the purposes of this guide, gel strength is the stress required to initiate flow in a fluid after standing. For assessment of the thixotropy of support fluids, gel strength is determined after rest times of 10 seconds and 10 minutes using a direct indicating viscometer such as a Fann type viscometer. It should be noted that yield stress is a notional stress invoked to model the behaviour of fluids in motion and not the stress required to initiate flow in a fluid at rest.

Mineral fluids used in deep foundation elements generally have modest viscosity and low gel strength. Addition of cellulosic polymer to mineral fluids may increase viscosity but not gel strength. Salt water clays such as attapulgite can have higher gel strength than bentonite at similar concentrations.

Although beneficial to excavation stability in coarse soils, gel strength values become significant above 5 N/m² [10 lbs/100 ft²] corresponding to a fluid that will suspend solids but with a significant rise in fluid density. For polymer

fluids with no appreciable gel strength, other approaches to solids management must be adopted.

The ideal value of gel strength is that which allows sand and larger particles to settle freely whilst finer particles remain in suspension to prevent sedimentation on the reinforcement cage. Given that particle size varies widely there is no ideal value of gel strength. Low gel strength fluids are therefore the most commonly used.

Gel strength should not be considered as a control criterion. It is, however, useful in fluid management procedures and gives a further indication as to what is happening with the fluid.

Use of Rheological Data

Although fluid rheology can have a profound effect on the performance of support fluids it is rare for rheological parameters to be used in design calculations (typically worst-case parameters are assumed, for example, a plant supplier may state: "this pump can handle fluids of viscosity up to" or "this soil-slurry separation plant can treat fluids with Marsh funnel times up to seconds"). Rheological parameters such as viscosity, yield stress and gel strength are assessed with standardised instruments and the results appraised against control specifications. Rheological parameters are typically control parameters not equipment design parameters (see Section 5.2 on Pumping).

Sedimentation in Support Fluids

The rate of sedimentation in a support fluid will depend on the size of the particle settling and the properties of the support fluid. Table 2 gives indicative settlement rates. The procedure used to develop Table 2 is given in Appendix D.

TABLE 2 ESTIMATED SPHERICAL PARTICLE SETTLING VELOCITIES IN M/HR (VALUES IN ITALICS REPRESENT REYNOLDS NUMBERS >1)

Soil type	Particle size	Particle size	Settling velocity in water, viscosity 1 cP	Settling velocity in a Newtonian support fluid of viscosity 15 cP	Settling velocity in PHPA polymer support fluid
	Microns	mm	m/hr	m/hr	m/hr
CLAY	2	0.002	<0.1	<0.1	<0.1
SILTS	6	0.006	0.12	<0.1	<0.1
	10	0.01	0.32	<0.1	<0.1
	20	0.02	1.29	<0.1	<0.1
	60	0.06	12	0.8	<0.1
SANDS	100	0.1	32	2.2	<0.1
	200	0.2	95	8.6	<0.1
	600	0.6	>200	78	4
	1000	1	>200	170	40
	2000	2	>200	>200	>200
GRAVELS	6000	6	>200	>200	>200
	10000	10	>200	>200	>200
	20000	20	>200	>200	>200

Note: Settling velocities less than 0.1 m/hr are shown as <0.1 as particles settling at velocities of 0.1 m/hr and less are unlikely to deposit any significant amount of material at the base of an excavation.

Similarly velocities >200 m/hr are shown as >200 as all particles with such velocities are likely to settle sufficiently rapidly that they are removed in normal base cleaning operations.

All diameters are Stokes diameters i.e. for non-spherical particles diameters are those of the equivalent spherical particle with the same settling velocity.

3.2 Support Fluid Tests

Control of support fluids requires a range of tests to be carried out as no single test can adequately describe the fluid. The various fluid properties are interdependent.

Rheological properties are rarely measured directly on site. A series of simple tests which reflect the rheological parameters are carried out as summarized in Table 3. The required range of parameters for these tests are often defined in Specifications such as EN 1536, EN 1538, ICE SPERWALL, ACI 336.1, FHWA and Caltrans. Currently used acceptance values are presented in Section 8.3. The test methods are described in detail in Appendix B.

TABLE 3 SUPPORT FLUID TESTS

Property to be measured	Test Method
Density (g/ml)	Mud balance or precision weighing
Viscosity (s/qt)	Marsh funnel
Sand content (% volume)	Sand content test
Filtration loss (ml after 30 min)	API fluid loss test
Filter cake Thickness (mm at 30min)	API fluid loss test
pH test*	Electrical pH meter or pH papers

Note: pH should be considered an indicator, not an acceptance control.

Portable fluid test kits can be readily obtained. A basic fluid test kit is fine for a crew on location to test basic fluid parameters. The advanced test kit (Figure 11) with the addition of the 2 speed rheometer is more suitable for a trained engineer to examine the rheological parameters of the fluid.

FIGURE 11 ADVANCED FLUID TEST KIT



Other tests are available for use in special circumstances and these are described in Appendix B.

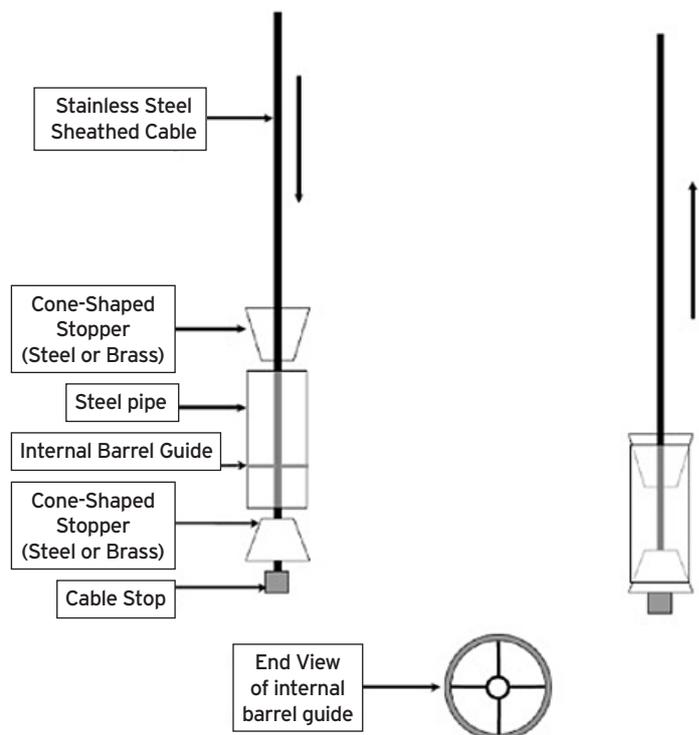
3.3 Sampling

In order to assess the variation of properties with depth within the excavation, it is necessary to sample the fluid at known depth(s). The minimum volume of the sample should be 2 litres.

There are many samplers available incorporating valves and flaps but the majority of these are made of plastic to reduce the weight. These lightweight samplers are often unable to penetrate the fluid near the base of the excavation due to its high density.

A simple steel sampler is shown in Figure 12. The sampler is suspended by a wire rope which has depth marks at one metre intervals allowing accurate assessment of depth. Due to the weight, the rope is normally wound on a drum at ground level, mounted on a support frame. The seals between the stoppers and the steel pipe must be tight to prevent loss of fluid. This is especially important when sampling polymer fluids.

FIGURE 12 SUPPORT FLUID SAMPLER





3 / Properties of Support Fluids

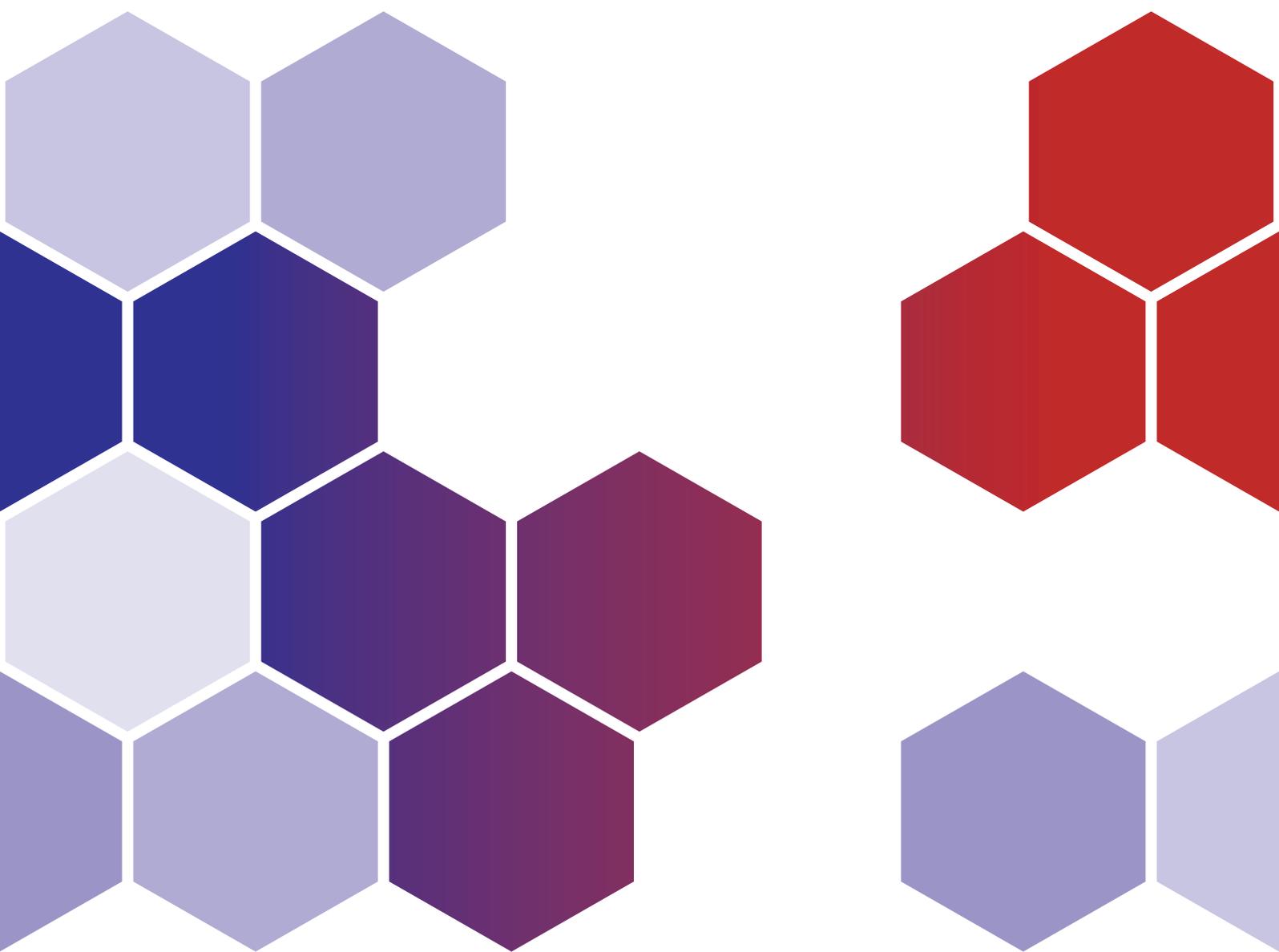
The base section is lowered to the required depth and the drum locked in position. The centre section is then allowed to fall down the wire rope. The top cap is then allowed to drop onto the centre section. The assembly is winched to the surface and the sample recovered.

Due to the weight of the base section (in the range of 5 kg or 11 lbs), it is possible to sample high density fluids at the base of the excavation.

The depth at which a support fluid must be sampled is rarely specified except "towards" the bottom of the excavation to determine the sand content so as to determine that it is below a maximum specification value without consideration of the entire fluid column. This is a very limited view of support fluid sampling, since waiting until the end of the excavation process to analyse the condition of the support fluid is equivalent to working in the dark.

Section 4

Raw Materials

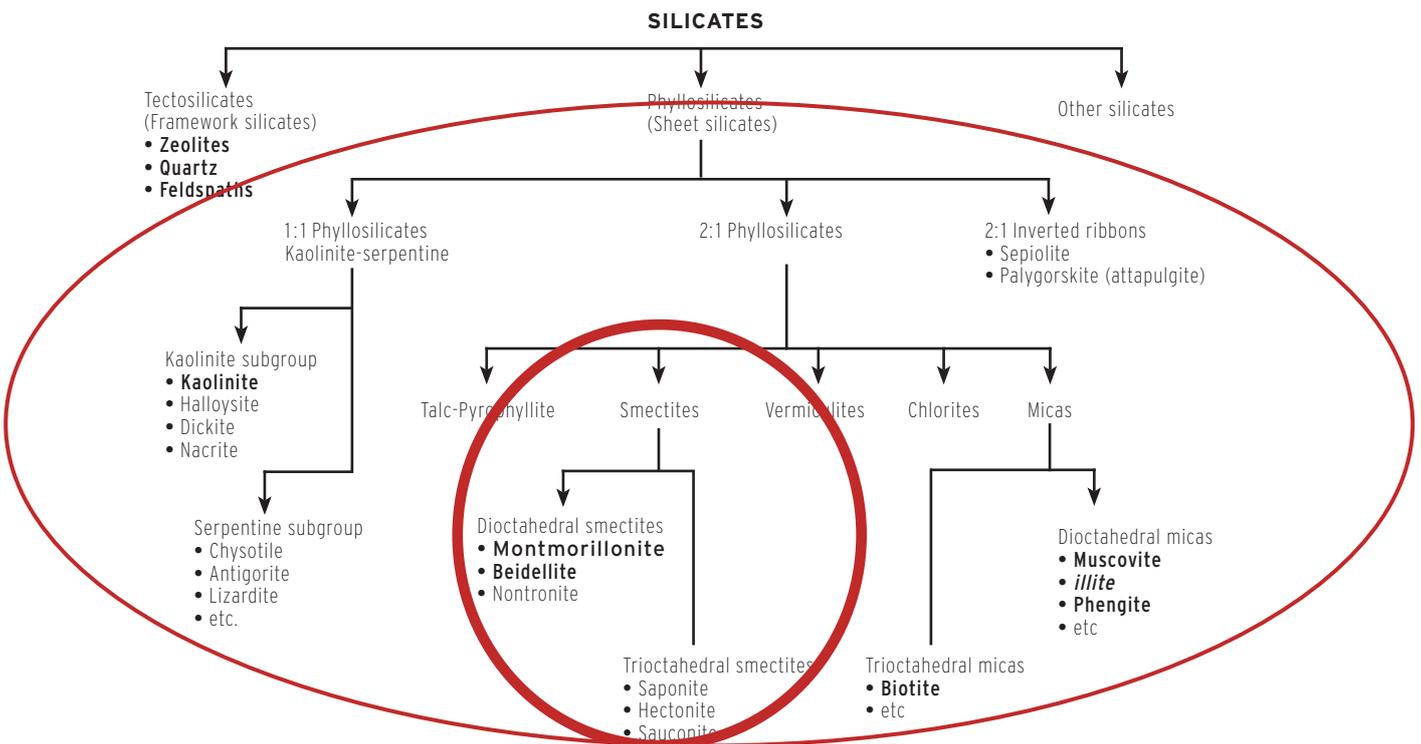


4.1 Bentonite

Structure and Composition

Commercial bentonite is composed predominantly of the clay mineral montmorillonite (which belongs to the smectite group) together with other types of smectite and other minerals (feldspar, quartz etc). The classification is summarised in Figure 13.

FIGURE 13 CLASSIFICATION OF SILICATES AND BENTONITES



The physical properties and characteristics of bentonite are dictated by the montmorillonite (Wright, 1968). In the majority of cases bentonites are formed by the alteration of volcanic ash and rocks after intense contact to water (Figures 14 and 15).

FIGURE 14 FORMATION OF CLAYS AND BENTONITES

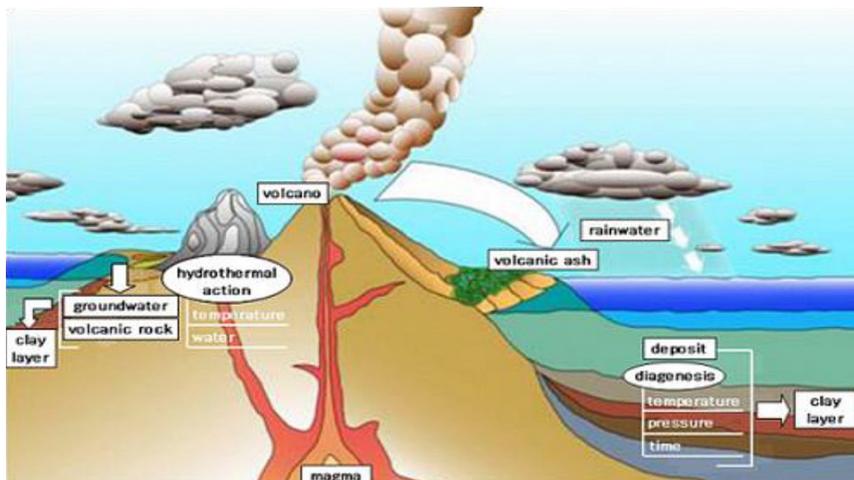


FIGURE 15 EXAMPLE OF A BENTONITE MINE



Minerals of the smectite group form platelets of a few microns in lateral dimensions but only a few Angstrom in thickness as shown in *Figures 16 and 17*. Individual platelets are composed of three layers, an octahedral layer comprising of Al, Mg, Fe, O and OH groups, sandwiched between two tetrahedral layers with Si-O₄ tetrahedrons. Through isomorphous substitution of divalent cations by monovalent cations (tri-octahedral smectites) or trivalent cations by bivalent cations (di-octahedral smectites) in the octahedral layer as well as Si by Al in the tetrahedral layer, a layer charge is generated. This layer charge is counterbalanced by mono- or divalent cations in the interlayer space which link the individual platelets into stacks.

Due to the weak charge of the crystalline layers, the interlayer cations, predominately Na, Mg and Ca, are exchangeable. One of the most abundant smectite minerals is the di-octahedral montmorillonite where part of the Al contained in the octahedral sheets is replaced by Mg and Fe, and further electrical charge is generated in the tetrahedral layer by the replacement of Si by Al.

FIGURE 16 STRUCTURE OF SMECTITE PLATELETS

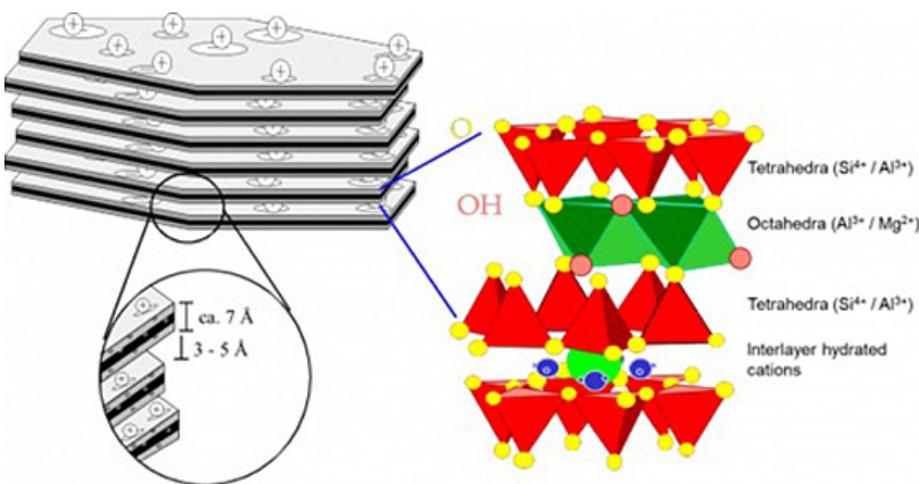
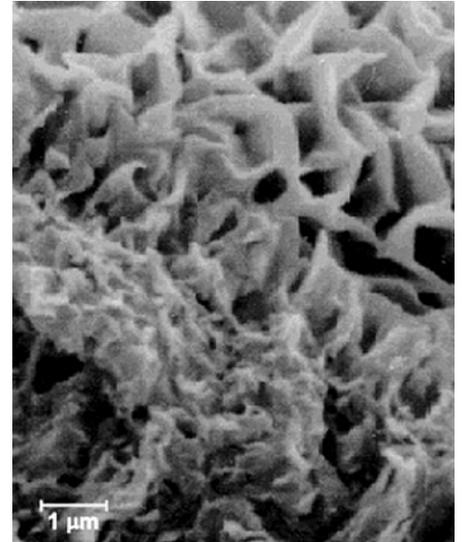


FIGURE 17 SMECTITE UNDER THE ELECTRONIC MICROSCOPE



In the natural state, bentonites with calcium (and sometimes magnesium) as the dominant exchangeable ion are the most abundant. Naturally occurring sodium bentonites are rare and are isolated to specific global locations e.g. Wyoming in North America.

The commercial bentonites available for support fluids are:

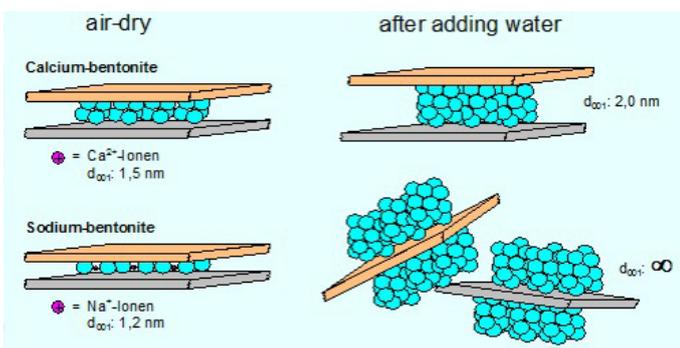
- Sodium bentonites (natural or activated) which are used in support fluids based on the local availability with essentially the same characteristics. Activated sodium bentonites are Ca or Mg bentonites that have been processed industrially to exchange the divalent Ca or Mg cations with Na⁻ ions by treatment with soda ash (sodium carbonate). During treatment Ca and Mg are precipitated after being replaced by Na⁻ ions from the readily soluble Na-carbonate. After modification these bentonites behave as sodium bentonites with high swelling and gelling behaviour.
- Bentonite modified by polymers: Many bentonites are treated with different polymers such as cellulose derivatives, polyacrylamides or gums to provide better rheological and filtration behaviour or higher stability in contaminated ground conditions for specific applications or projects.

Colloidal Properties of Commercial Bentonites

The most important property of smectite clay minerals for deep foundation construction is the swelling on contact to water and the creation of a stable colloidal suspension. This happens with the increasing availability of water, the hydration of the ions in the smectite interlayers resulting in a gradual widening of the interlayer space and, depending on the amount of water available, two, three or four molecular water layers which may penetrate between the silica layers (Figure 18).

Specifically in the presence of Na^+ , a complete dispersion into isolated layers (silica-alumina-silica units) or thin packages of a few layers can occur in water or electrolyte-poor solutions (swelling towards infinite dispersion) so producing colloidal sized particles and a colloidal suspension.

FIGURE 18 INTERVAL BETWEEN LAYERS OF CALCIUM AND SODIUM MONTMORILLONITE



This inner-crystalline swelling can be observed by an increase in volume of the clay minerals which can be many times the original volume. Sodium montmorillonites can store large amounts of water in the interlayers and on the clay mineral surfaces. Accordingly, a large swelling volume is observed.

The colloidal properties of such bentonite dispersions are controlled by the electrical forces generated within the clay mineral platelets and any dissolved and adsorbed electrolytes resulting in a very large specific surface area as high as $750 \text{ m}^2/\text{g}$ [$260 \text{ ft}^2/\text{oz}$]. Free swelling, the resulting high surface area and a negative layer charge provide desired gelling and sealing properties, binding behaviour, and preferred adsorption of cationic molecules.

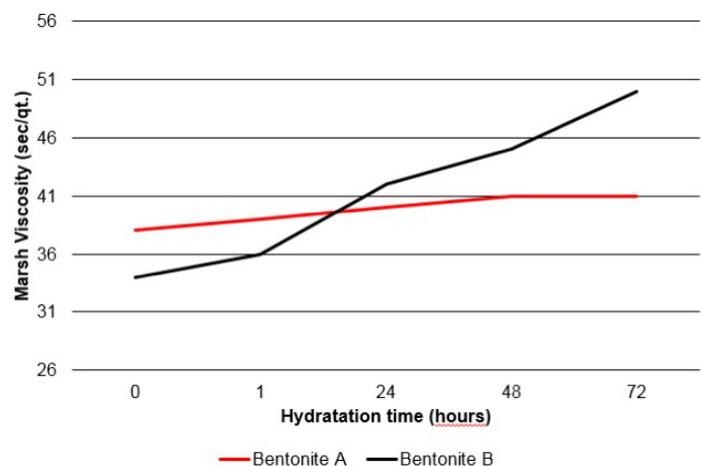
Clay mineral dispersions with high solid content do not show Newtonian behaviour, rather they show plastic flow behaviour (see Figure 9). Plastic flow behaviour is characterised by the appearance of a yield stress (Kelessidis, 2017). In the case of bentonite suspensions, proportionality between shear stress and shear rate is typically reached only at high shear rates or not at all.

The flow behaviour of a sodium bentonite dispersion is determined by a number of factors, including (Vail & Bachmann, 1988):-

- proportion (concentration of clay minerals in the dispersion)
- features of the clay mineral particles
 - morphology and surface
 - degree of delamination and size
 - layer charge and hydration potential
- interactions among particles
 - type of counter ions
 - concentration of each counter-ion type
 - pH value
 - additives, such as poly-anions

Depending on the intrinsic properties and the origin of the bentonite, there is a time-dependent flow behaviour of bentonites fluids. Some bentonites reach the maximum viscosity in a few minutes after mixing and others require several hours or even days (Figure 19).

FIGURE 19 TIME DEPENDENT HYDRATION PROCESS OF A 40 SEC/QT MARSH BENTONITE SUSPENSION



These properties are also strongly influenced by the constituents of the makeup water (see Section 4.6).

Supplier Documentation

Bentonite suppliers must supply the Technical Data Sheet and the Material Safety Data Sheet of the product being supplied for the works.

The technical data sheet provides information about the product and its performance. The testing conditions shall be clearly described and in particular if they differ from the usual API standards.

It is **essential** that the Supplier defines the type of makeup water, the mixing and hydration time considered for the measures as well as the mixing device used to prepare the suspension. These parameters influence the overall properties of the bentonite suspension as illustrated in *Sections 4.6 and 5.1*.

The end-user needs to carefully read this documentation since the performances obtained on site can differ greatly from those given in the Technical Data Sheet. This is particularly true when values have been measured on a suspension prepared according to API procedures i.e. with distilled water as the makeup water, after long hydration time (e.g. 16 hours) and high shearing conditions (20 minutes using a Hamilton Beach device at 20,000 rpm).

The choice of a bentonite cannot be made based only on the Technical Data Sheet. This document rarely provides precise information about the evolution of the bentonite performance e.g. Marsh viscosity, filter loss value and yield point at different concentrations and with different makeup waters or exposed to typical chemical contamination e.g. cement contamination. If required, complementary laboratory tests should be carried out together and/or in parallel with the supplier to develop a complete overview of the product's performance under actual site conditions allowing a safer approach for designing the supporting fluid.

Bentonites for support fluids can be classified according to their volume yield and chemical type as proposed by the American Petroleum Industry (API) e.g. natural sodium bentonite, activated sodium bentonite or non-treated bentonite.

In the case of deep foundations works, this type of classification does not help the contractor selecting the right bentonite quality mainly due to the absence of properties measured in representative site conditions e.g. properties of the makeup water and mixing time.

Some bentonite producers have worked closely with contractors to define more representative laboratory testing conditions enabling the documentation to be more comprehensive and adapted the Technical Datasheet for specific customers.

Bentonite suspensions are then prepared using tap water as the makeup water with an average electric conductivity of 500 to 600 $\mu\text{S}/\text{cm}$.

The dispersion and mixing of bentonite is achieved by means of a Rainery type mixer equipped with a 80mm diameter deflocculating turbine rotating at 1500 rpm.

Mixing time should not exceed 3 minutes to reflect construction sites conditions.

Measuring the viscosity i.e. Marsh viscosity and/or direct-indicating, rotational viscometer as well as other performance criteria such as filtrate loss, filter cake thickness or bleeding can be done immediately after mixing, 1 hour and 24 hours to highlight the behaviour of the product with ageing. This identifies any requirements to store the bentonite fluid before use in case of slow swelling bentonite.

Additional performance tests can be added to illustrate the behaviour of the bentonite in the presence of contaminants e.g. cement or salt.

Providing information on the minimum concentration of bentonite needed to achieve fluid acceptance criteria under actual site conditions should then be preferred to the use of volume yield as used in the Oil and Gas Industry.

FIGURE 20 HAMILTON BEACH MIXER (LEFT) AND RAYNERI MIXER (RIGHT), FOR LABORATORY USE ONLY



4.2 Polymer

There are hundreds of different polymer products approved for use in the Oil and Gas Industry. Only those types commonly used in deep foundation construction are considered in this Section.

Polymers, whether natural, modified natural or synthetic, have been extensively used because of their ability to reduce fluid loss and minimize swelling in clays.

Polymer fluids may use a single type of polymer although blends of polymer may be attractive to enhance

the fluid capabilities. Multiple charge polymer systems (anionic, nonionic and cationic) are now available that can deliver additional performance aspects depending on the soil conditions.

Polymers are available in dry powder form taking 30 minutes to an hour to fully hydrate depending on temperature and make-up water quality. Polymers are also available in water/oil emulsion or in brine emulsion. Liquid polymers are easier to use at the preparation level with a quick development of viscosity but are more expensive on a weight of polymer basis. Also in the case of the water/oil emulsion, some of the emulsion weight is mineral oil with some surfactants. This may be an issue at the time of disposal.

Natural Polymer (Gum)

Guar gum has been in use in water well drilling since the advent of auger bucket drill rigs. Guar gum derivatives such as hydroxypropyl guar (HPG) have also been utilized on a regular basis. Guar and HPG are good products wherever a risk of major support fluid loss exists since it permits easy cross-linking which turns the fluid into a thick gel.

Xanthan gum (additive) is a manufactured gum based on bacterial cultures and the pre-cursor of a series of gums developed first for the oil field (e.g. Diutan Gum) ^(Rogers, 1963) but which have found applications in the ready-mix concrete industry especially as anti-wash agents (AWA) for under water work and self-leveling concrete. Some of these polymers are expensive but can act as a bentonite substitute with a strong pseudo-plastic behaviour and with the ability to carry sand and fines which is an opportunity to have heavier polymer fluids. The molecular weight remains in the low range making these support fluids compatible with conventional solids separation plants. Xanthan gum is readily biodegradable and may have to be used in conjunction with a preservative. Xanthan gum may turn into a gel when contaminated by calcium.

Modified Natural Polymer (CMC and PAC)

Polysaccharide polymers are in the group of cellulose polymers. These polymers can be nonionic or anionic. Carboxymethylcellulose (CMC) is the main type of polymer used in several industries and is essentially a good viscosifier which can also improve fluid loss control with various degrees of molecular weights, degrees of substitution and viscosities. CMC's with a degree of substitution of one or above are called poly-anionic cellulose (PAC), have an anionic charge and are also available in a variety of molecular weights.

All these polymers are considered bio-degradable but with much less sugar content the bacterial degradation is much deferred by comparison to a guar gum and are therefore safe ingredients for support fluids. In the past, CMC's were used only as additives to mineral fluids as a fluid loss reduction agent.

Cellulosics such as CMC and HEC (hydroxyethylcellulose) provide viscous fluids without any significant gel strength although they offer good lubricity. They will combine with mineral particles (bentonite, soil etc.) to form a homogenous fluid while allowing all other particle sizes to settle. Such support fluids produce very thin filter cakes and good fluid loss control by allowing suspended fines to participate in the filter cake formation.

Pure polymer support fluids with cellulosic derivative have been successfully used with hydromills, offering a suitable fluid for drilling, supporting the excavation, controlling filter cake and fluid loss in the formation, managing solid controls due to the ability of the polymer to withstand centrifugal pumps, hydrocycloning and passing through screen shakers. When using cellulosic polymer with the hydromill, the methodology is driven by the reverse circulation process, and similar fluid performance during excavation, for re-use and before concreting (viscosity, density, sand content, filtration/cake) to a bentonite system are required. This is important to note as it is a major difference between PHPA and natural modified polymers.

Synthetic polymer (PHPA)

Partially hydrolyzed polyacrylamide (PHPA) polymer has become the most common type of polymer used in the Oil and Gas Industry. These are sometimes referred to as HPAM. Although a wide range of molecular weights are now available, most users are attracted by the highest molecular weight for its ability to generate high viscosities. The higher the molecular weight, the better the encapsulation of clays and the cleaner the support fluid. These polymers are anionic with a variable charge level that is independent of the molecular weight. This charge also has a major role in preventing the dispersion of clay particles. While higher molecular weight PHPA's function well for bored piles (drilled shafts) and diaphragm walls excavated with a grab, they do not function well with hydromills. High molecular weight PHPA's will "blind off" the solids separation equipment associated with hydromills. This results in a reduction of the solids separation equipment's ability to remove solids.

Co-polymerization with vinyl or acrylate and other grafting on the polymer chains adds complexity to the polymer arrangement and branching and can now change the basic characteristics of the fluid, especially if used in combination with cationic materials. Fluid loss control, fines control, shear stability and resistance to environmental contaminants such as salt, VOC's, hydrocarbons and heavy metals can be improved dramatically.

A viscous high molecular weight PHPA is still a lightweight fluid with a specific gravity close to that of water that alone without suspended solids does not form a filter cake for fluid loss control but can impart various gel strengths depending

on the additives and the characteristics required. Originally, the “long chain” strands of polymer fluid would not permit the use of reverse circulation systems using a conventional solids separation plant with shaker screens. This is no longer the case as polymers are now available, generally of lower molecular weight, that are more shear stable and can be used in conjunction with conventional solids handling equipment.

4.3 Blended Fluid

The concept of blending mineral particles with polymer goes back to the late 1960's. The idea is to realize a blend to create a support fluid with benefits from both materials giving more design flexibility for the conditions anticipated on a specific worksite.

Mixing of a clay fluid with a lower molecular weight polymer fluid is a way to realize the advantages of these polymers while minimising the inherent risks associated with them with the creation of a low permeability filter cake. The presence of hydrated bentonite particles combining with suspended fines allows for the formation of a filter cake. In this case, the polymer must be a lower molecular weight polymer so that flocculation is limited. The continuous phase is the polymer fluid and the suspended bentonite or other clay particles acting exclusively as plugging agents in the filter cake formation process.

A mixture of mineral particles (e.g. clays and limestone fillers) can be used with high molecular weight synthetic polymer in order to increase the fluid density or help to prevent fluid loss into the formation.

Another possible option consists in associating a polymer to a commercial bentonite to form a bentonite polymer blend where the bentonite remains the continuous phase and the polymer helps in improving the rheological properties, fluid loss properties and/or resistance to chemical pollution. Pre-blending can be carried out by the supplier or be implemented on site at the batching plant. It is important to note that many of the bentonite materials being offered are already “blends”. To improve the rheological properties of some bentonites and to meet API specification 13A section 5, they have been “beneficiated”. “Beneficiated” bentonites have up to 5% polymer by weight of bentonite added to them when packaged. Therefore, polymer is already present in the system at normal usage levels without the separate addition of polymer.

Blending both mineral particles and polymer requires experience in the design of the fluid to avoid changing the polymer fluid from an active polymer solution to a clay water suspension with no active polymer – a state that is not identifiable by any of the conventional tests. If this is

allowed to occur, soil cuttings can freely disintegrate, thus exacerbating the sorption situation, increasing density and viscosity and promoting sloughing and swelling of the side-wall soils if the formation is water sensitive.

4.4 Environmental Considerations

The use of support fluid requires careful consideration of the environment in which it will be applied. Prior to any project it is mandatory to perform an environmental assessment of:

- health and safety in manipulating, handling and storing materials
- environmental impact of the support fluid on the soil and groundwater
- handling, storage and disposal of the support fluid and excavated materials

At the preliminary stage of a project, it is important to analyse the situation by considering the type of deep foundation to be installed, the geometry of the site, the ground conditions (physical and chemical parameters of the soil), the groundwater and surface water chemistry, sensitivity to environmental impact (water production, rivers, sea etc.) and the potential previous or preliminary treatment of the soil (e.g. anthropic pollution, ground treatment such as pre-grouting or soilmixing).

Through the analysis of environmental regulation and site conditions, the choice of drilling fluid materials and additives can be made by considering:

- the technical performance of the fluid
- the minimisation of fluid volumes (fluid losses into the ground)
- the environmental impact of the selected fluid and additives through local regulations
- the impact and reaction of the ground to the support fluid
- the most appropriate way to dispose of excavated materials and waste support fluid, as well as drained and dirty water produced at the site

Health and safety considerations to limit risk to workers must be part of the Health and Safety Plan. Risk assessments should be carried out prior to execution based on the Material Safety Datasheets for all components of the support fluid. Contaminated ground must be also integrated in the Health and Safety Plan as this contamination will transfer to the support fluid with a risk to workers.

The use of support fluid, handling and storage of waste fluid and excavated material as well as disposal is driven by local environmental regulation such as the Water Framework Directive and local wastewater treatment regulations.

The impact of soil and groundwater on the support fluid properties will greatly influence the choice of materials and additives as well as the rate of use of the drilling fluid. As a consequence this will also have an influence on the environmental impact and disposal of the waste fluid. The impact of the soil and groundwater can be evaluated as:

soil and groundwater containing chemicals over permissible thresholds that might affect support fluid properties (calcium, magnesium, acids, salts and organics)
soil and groundwater classified as contaminated according to local environmental regulations

When considering the environmental impact of the support fluid to the surrounding ground, it is not only important to consider the risk associated with the materials entering into the composition of the support fluid but how these materials might change the physical chemistry of the soil and groundwater. The minimization of fluid loss into the formation is a key parameter to reduce potential environmental impact. Risks to be evaluated will range from accidental spills, handling and diverting "dirty" waters, and temporary and long term impact on the groundwater chemistry.

Both groundwater and surface water receptors will be classified in terms of sensitivity. This will vary from highly sensitive locations such as in or near groundwater abstraction zones, decreasing with distance from the abstraction point. In addition, the use of fluids in ground near sensitive surface water is more difficult if there are direct pathways compared to areas with cohesive soils that may prevent migration of fluids. Local regulatory policy should be complied with. Typically, the local regulator will set various zones around drinking water abstraction points and some activities may be prohibited or very restricted within the closest protection zones. It is likely that the amount of assessment required in more sensitive locations will be greater and more likely to require quantitative data, rather than qualitative.

It will also be necessary to consider the contamination status of existing soils and water in the area where the support fluids are to be used, as the construction process may create new pathways for existing contamination to migrate to sensitive receptors.

In some cases, when using support fluids of some types in highly sensitive settings, it may be necessary to implement a programme of groundwater monitoring to demonstrate that there is no significant impact (for non-hazardous pollutants) or discernible release (hazardous substances).

The environmental impact of bentonite, polymers and additives is not only based on information given in the Material Safety Datasheet or from eco-toxicological data. Environmental impact should be assessed based on leachate

potentials and changes in concentration in the groundwater, both short and long term, compared to maximum acceptance concentration levels derived from local environmental standards. Maximum concentration levels will vary depending on the sensitivity of the receptor site.

The same approach applies when dealing with disposal of excavated materials and waste fluid. Both the nature of material and its chemical composition (such as organic content, total organic carbon, heavy metals, hydrocarbons) must be considered. Care must be taken with biodegradable materials that may not be considered inert on a short term basis. Waste fluid with high solids content and excavated soil with high moisture content may require disposal to special treatment facilities with high cost. Leaching tests are normally required to determine whether pollutants can be released from the materials.

4.5 Choice of the Fluid Type and Cost Evaluation

The support fluid selection is not only based on soil conditions, but also on the practicality of the fluid system, the technical level of the personnel, the environmental issues and the disposal conditions.

When choosing the preferred support fluid, the following should, as a minimum, be considered:

- project and site dimensions: diameter, width, length and depth of foundation elements to be constructed
- equipment (excavation, pumping, treatment etc.) and the length of casing (if used)
- excavation method (static drilling or reverse circulation drilling)
- soil conditions: geotechnical profile (e.g. type of soils, permeability, cohesion and chemistry), groundwater level and chemistry
- make-up water quality
- fluid requirements: ease of use and proven effectiveness in the soil conditions
- environmental issues (known contaminants and obstacles)
- disposal requirements/restrictions
- supply chain
- economics

Tables 4 and 5 present indications of appropriate drilling fluids related to the method of construction and the soil type.

TABLE 4 SUPPORT FLUID CHOICE RELATED TO EQUIPMENT TYPE

Fluid Type	Common Examples	Method of Excavation				
		Grab	Hydromill	Auger / Bucket (Kelly)	Reverse or Direct Circulation	Trench Drains
Water		X	X	X	✓✓✓	X
Mineral	Natural Sodium Bentonite Activated Sodium Bentonite	✓✓✓	✓✓✓	✓✓	✓	X
Natural Polymer	Gum Polysaccharide	X	X	X	X	✓✓✓
Modified Natural Polymer	CMC PAC	✓	✓✓	✓	✓	✓✓
Synthetic Polymer	PHPA Vinyllic	✓✓✓	-	✓✓✓	✓	✓

✓✓✓ ideal ✓✓ acceptable ✓ possible X not recommended

There is no universal fluid for all projects and selection of the right product(s) has to be made after considering all the above parameters. As an example, bentonite support fluids are not optimal in chemically aggressive grounds or clayey soil with the need for increased fluid management. Polymer fluids may perform better in such conditions. On the other side, polymers may not be optimal in open soils (fill, fissured ground, open gravels) because of their lack of gel strength. This may be remedied with clogging agents such as water swellable (but not soluble) polymers.

Choosing the right support fluid for each occasion provides a flexible and broad solution proven able to solve a wide range of challenges not only related to geological conditions (e.g. fluid loss in limestone fractures or fluid loading in clays) but also related to the entire productive cycle. Table 5 gives examples of suitable support fluids depending on soil type. The Table aims to ensure that the fluid is able to manage stability issues such as maintaining sufficient head pressure for all formations, limit fluid loss in the formation for boulders/cobbles/gravels/coarse sand, and limit hydration or sloughing in fine soils and swelling clays.

TABLE 5 SUPPORT FLUID CHOICE RELATED TO SOIL TYPE

Soil Type	Bentonite		CMC/PAC		PHPA		Comments
	Static	Reverse Circulation	Static	Reverse Circulation	Static	Reverse Circulation	
Rock	✓	✓	✓	✓	X	X	no stability issues
Boulders/Cobbles	?	✓	X	X	X	X	fluid loss / head
Gravels	✓	✓	X	?	X	X	fluid loss / head
Coarse Sand/Gravel	✓	✓	?	?	?	X	fluid loss / head
Medium/Fine Sand	✓	✓	✓	✓	?	X	head / low cohesion
Silty/Clayey Sand	✓	✓	✓	✓	✓	X	head / low cohesion
Clay	✓	?	✓	✓	✓	X	head / low cohesion
Hard Clay/Limestone	?	?	✓	✓	✓	X	no stability issues
Swelling Clay	?	?	✓	✓	✓	X	head / soil hydration (sloughing)

✓ applicable X nonapplicable ? to be evaluated

Note: Using additives is a way to enhance each type of fluid listed to extend its application in the different soil types (especially those marked with a '?')

Concentrations

For bentonite support fluid, the concentration is typically in the range of 20 to 60 kg/m³ [35 to 100 lbs/cy] of water (2% to 6%) to achieve the fresh fluid criteria (see *Section 8.3*). The dedicated plant includes high shear mixer(s), hydration tanks and a fluid recirculation system. A bentonite fluid does not develop its properties immediately on contact with water and time for hydration (between 4 and 24 hours) should be allowed between mixing and use. The hydration time will depend on the type of bentonite and the level of shear in the mixer.

Drilling bentonites can be classified according to their volume yield and chemical type as proposed by the American Petroleum Industry e.g. natural sodium bentonite, activated sodium bentonite or non-treated bentonite. For deep foundations works, this type of classification does not help the contractor selecting the right bentonite quality mainly due to the absence of properties measured in representative site conditions e.g. make up water quality is rarely distilled water on jobsite and mixing time does not exceed a few minutes.

Some bentonite producers have worked closely with specialty contractors to define more representative laboratory testing conditions enabling the documentation of more comprehensive and adapted Technical Datasheets for their customers:

- bentonite suspensions are thus prepared using tap water as the makeup water with average electric conductivity of 500 to 600 $\mu\text{S}/\text{cm}$
- the dispersion and mixing of bentonite is achieved by means of a Rainery type mixer equipped with a 80mm diameter deflocculating turbine rotating at 1500 rpm
- mixing time should not exceed 3 minutes to reflect construction sites conditions
- measuring the viscosity i.e. Marsh viscosity and/or Fann viscosity as well as other performance criteria such as filtrate loss, filter cake or bleeding can be done immediately after mixing, 1 hour and 24 hours to highlight the behavior of the product with the aging. It actually helps anticipating the need to store the bentonite fluid before its usage in case of slow swelling bentonite quality
- additional performance tests can be added to illustrate the behavior of the bentonite in the presence of cement or salt contamination.
- providing information on the minimum concentration of bentonite needed to reach a practicable Marsh viscosity value in the actual site conditions should then be preferred to the use of the volume yield as defined for the Oil and Gas Industry

Modified natural polymer is used with a concentration of 1.5 to 5 kg/m³ [2.5 to 8.5 lbs/cy] (0.1% to 0.5%) prepared in the same way as the bentonite fluid but with a faster time for hydration.

PHPA polymer fluids are typically used at a concentration of 0.5 to 2 kg/m³ [0.8 to 3.5 lbs/cy] (0.05% to 0.2%) i.e. about 25 to 50 times less than bentonite. High shear mixing is not required and should be avoided as the polymers for excavation work are of high molecular weight and can be easily damaged ^(Lam et al. 2010).

Chemical Adjusters

The chemical adjusters may be those added to the makeup water to treat it or raise its pH (sodium carbonate, alkali hydroxides), or those used during the whole excavation process to restore the support fluid properties (fluidifier, dispersant, additional raw material etc.).

The disposal can require other products such as flocculants and coagulants, oxidising agents, bleach, etc.

Usage Rate

The usage rate is the ability of the support fluid to be used many times when mixed and treated properly. The rate is dependent on many factors including the soil conditions, the method of excavation and the efficiency of operations. Typically, 1m³ of support fluid can be used to excavate between 1m³ and 3m³ of soil. When the ground is polluted with cations or contains clays or there is substantial loss of bulk fluid loss into the ground (e.g. in fissured chalk) the usage rate can drop to less than one.

This usage rate enables calculation of the total volume of support fluid that the site will have to produce and manage.

Costs

The final in-use cost of a support fluid is not just a matter of raw material costs. Many parameters have to be considered from the outset of a project including (but not limited to) the following:

- raw material cost (per ton or cubic metre)
- volume yield of the raw material (quantity of raw material per cubic metre of fluid with suitable properties)
- chemical adjusters (for pre-treatment, in-use treatment, and disposal)
- makeup water cost (mains water, ground water, seawater)
- usage rate of the support fluid (losses to the ground, losses with excavated soil, aggressiveness of soil or contamination present in the soil)
- dedicated equipment costs (pumps, desanders, desilters, centrifuges, filter presses, storage tanks etc.)
- disposal costs for excavated materials and waste fluid (out of specification fluid and at end of project)
- logistical requirements for equipment and products
- productive cycle speed
- post installation remedial work and associated costs

4 / Raw Materials

An indication of the relative costs for material, labour, equipment and disposal is given in *Figure 21* (bentonite) and *Figure 22* (polymer) for various soil conditions.

FIGURE 21 RELATIVE COSTS FOR BENTONITE FLUIDS RELATED TO SOIL TYPE

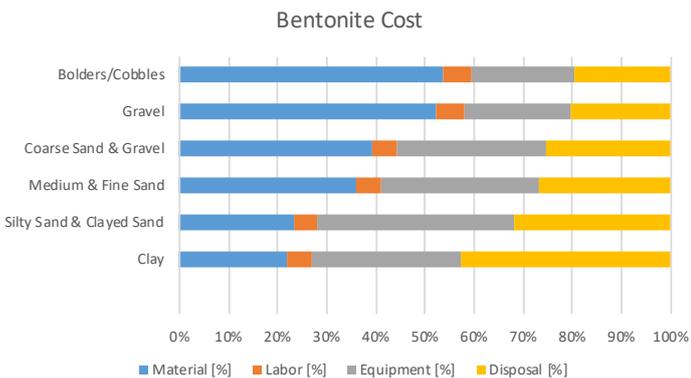
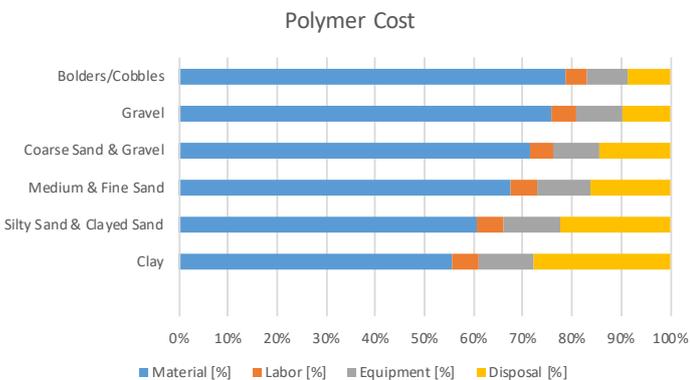


FIGURE 22 RELATIVE COSTS FOR POLYMER FLUIDS RELATED TO SOIL TYPE



- reclaimed water
- processed water containing residual flocculants

It is always advisable to have the source water tested prior to utilisation. This can be performed by most local laboratories who should test for pH, conductivity (total salt content), chlorides, calcium, magnesium, chorine, coliform, heavy metals and hydrocarbons. If the source is a municipality, they will have recent test results.

Bentonite

The properties of a bentonite suspension are strongly influenced by the constituents of the make-up water and in particular the electrolyte content and to a certain extent the presence of organics (Permien & Lagaly, 1995).

There is a direct relationship between the viscosity and the filtrate loss value with the conductivity of the make-up water as illustrated in *Figures 23 and 24*.

FIGURE 23 EXAMPLE OF THE EFFECT OF DIFFERENT MAKE-UP WATER QUALITIES ON MARSH VISCOSITY

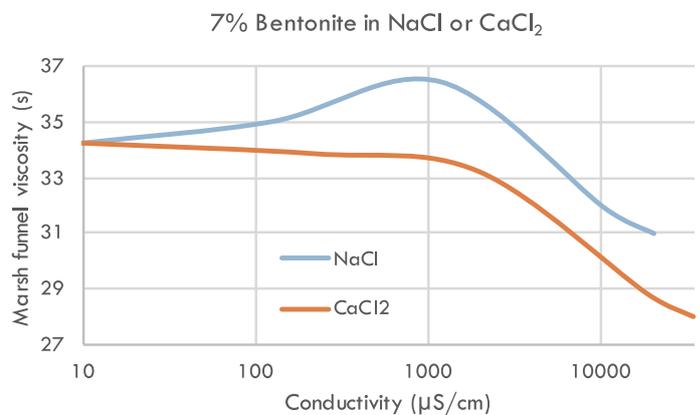
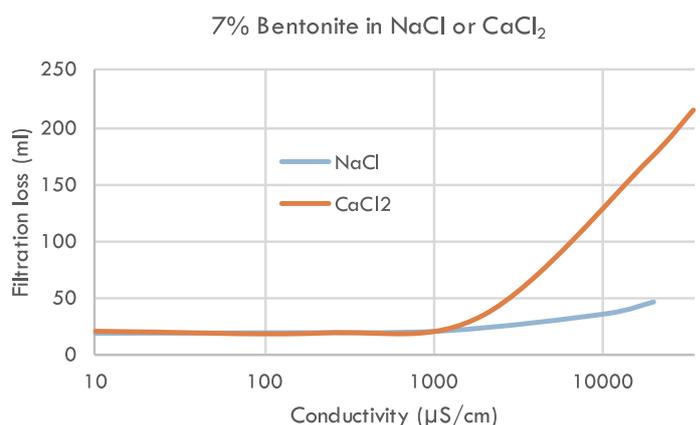


FIGURE 24 EXAMPLE OF THE INFLUENCE OF THE WATER QUALITY ON FILTRATION LOSS



4.6 Make-up Water

The make-up water has a major influence on the quality and performance of the support fluid. When evaluating the quality of the make-up water, the following should be considered:

- source: hydrant, river, pond, pumped well, seawater
- is it a continuous source and is the chemical composition consistent?
- hardness
- salt content: salt water, mains water, brackish water (10 to 15,000 ppm), seawater (up to 36,000 ppm)
- pH: below 6.5 or above 11.5 requires water treatment or increased polymer dosage
- contaminants: hydrocarbons, heavy metals, chlorine and bacteria

Particular attention should be given to the choice of the make-up water with a preference for water exhibiting low to medium electrolyte contents. This is generally the case for mains water when available.

Alternative water such as groundwater, river or lake water can also be used assuming the electric conductivity remains below 1500 $\mu\text{S}/\text{cm}$ otherwise a series of tests with various concentrations of the bentonite involved is highly recommended. pH and hardness (calcium and magnesium content) should be tested to anticipate the effect on the dispersion and swelling properties of the bentonite.

Depending on the site conditions, customized solutions can be found to optimise the use and the volume yield of the bentonite e.g. preparation of highly concentrated bentonite fluid in mains water diluted with groundwater to minimize the impact of the electrolytes from the groundwater, or chemical treatment using a pH buffer when the pH and/or water hardness dictates.

Polymer

Make-up water quality will always influence the final polymer dosages required to achieve the specified fluid viscosity. The softer the water, the higher the viscosities achieved with lower dosages and the harder the water, the more polymer is required to achieve the specified viscosity. If the water is coming from a natural source such as a stream or pond, the level of organics and contaminants must be considered. In some areas, fresh water is mixed with seawater to the hydrant system so brackish water is delivered. Some hydrant water is still supplied through old piping and can deliver elevated levels of iron in suspension.

Even with a chemical analysis it can be difficult to assess whether a water is suitable for use as a mix water. Most polymer suppliers will welcome a water sample to prebuild their system in to ensure that there will be no issues. The supplier can then advise the polymer concentration required to achieve the specified viscosity of the fresh support fluid.

The properties of PHPA fluids can be influenced by the presence of salt both in the mix water or in the ground. The salts may impact at the initial phase during hydration and have little effect on viscosity after or it may initially influence the hydration development and still persist to damage the chain through time. Sometimes some ions can enhance the viscosity stabilization through time and be beneficial for fluid viscosity maintenance.

The degree of partial hydrolysis of a PHPA can vary between polymers. Manufacturers will choose the degree to adjust the specific properties of the polymer solutions. If the degree of hydrolysis is too large, its properties are overly sensitive to salinity and hardness. The viscosity-increasing feature is derived from the repulsion between polymer molecules and

the segments of the same molecule. This repulsion causes the molecule to lengthen and snag on other molecules.

The molecular weight and the degree of anionicity or cationicity determines the salt impact as these interact with the chain. Some ions have an immediate impact on initial viscosity development and then after becoming neutral to the polymer chain not hindering further or affecting the hydration or viscosity maintenance. Some other salts impact viscosity with a lag in time. The larger the salt content the lower the viscosity. Specific salts will in general affect the amount of product required to develop and maintain viscosity of the fluid. Above these ranges the fluid requires a higher mixing rate in kg per m^3 to cope with the salt interaction and maintain its properties.

Once salts are compensated with a balanced amount of polymer, viscosity is normally maintained except where subject to cyclic exposures to the salts. The exposure of the fluid to cyclic additions of salt increases the fluid viscosity and pH changes. These cyclic additions are normally found in the makeup water, saline ground soil or by concrete contamination.

Natural and modified natural (e.g. CMC and PAC) polymers are usually tolerant to salts. Some synthetic polymers are available which are tolerant to salts. These combine specific networks of space arrangements and components of backbone strength which improves the regularity of the bulk molecule structure providing better salt tolerance performance. These can be modified versions of PHPA which have hydrophobic groups attached to the backbone. Other modifications are available as raw products or blends to inhibit or reduce the salt influence on the polymer performance.

In conclusion, the choice of the make-up water has a direct impact on the fluids mixing ratio but does not necessarily affect its performance provided the ratio is adjusted in accordance with the salt content impacting the polymer.

4.7 Water Without Addition of Bentonite or Polymer

Water may be suitable without the addition of bentonite or polymer in some specific conditions. It is more frequently used for bored piles (drilled shafts) than diaphragm walls.

Whilst water is cheaper to supply than other support fluids, its use is limited to ground formations that are stable enough not to slough during drilling. This is because the clean water does not form a low permeability filter cake at the excavation face. Hence it is difficult to maintain a net fluid pressure in the excavation. This means the water pressures in the soil are similar to the water level in the casing. Even with arching effects, the effective stress in the soil drops to zero and

the soil could slough into the excavation. Water without additions should therefore only be used in stiff clays, rock formations or with temporary/permanent casings.

Casings may be partial or over the entire length of the drilled hole. The casings must be well sealed into the underlying stable ground or rock to ensure that soil does not unravel from behind the casing toe into the drilled hole during excavation. This unravelling can lead to cavities forming behind the casing which have the potential to cause mixing of soil and water with concrete during the casing removal. These problems can also be encountered when the casing is advanced through unstable soil layers. A plug of soil within the casing may be required and/or excavation is not carried out below the toe of the casing.

Where adjacent buildings or services are present it is important to monitor settlements during the deep foundation installation.

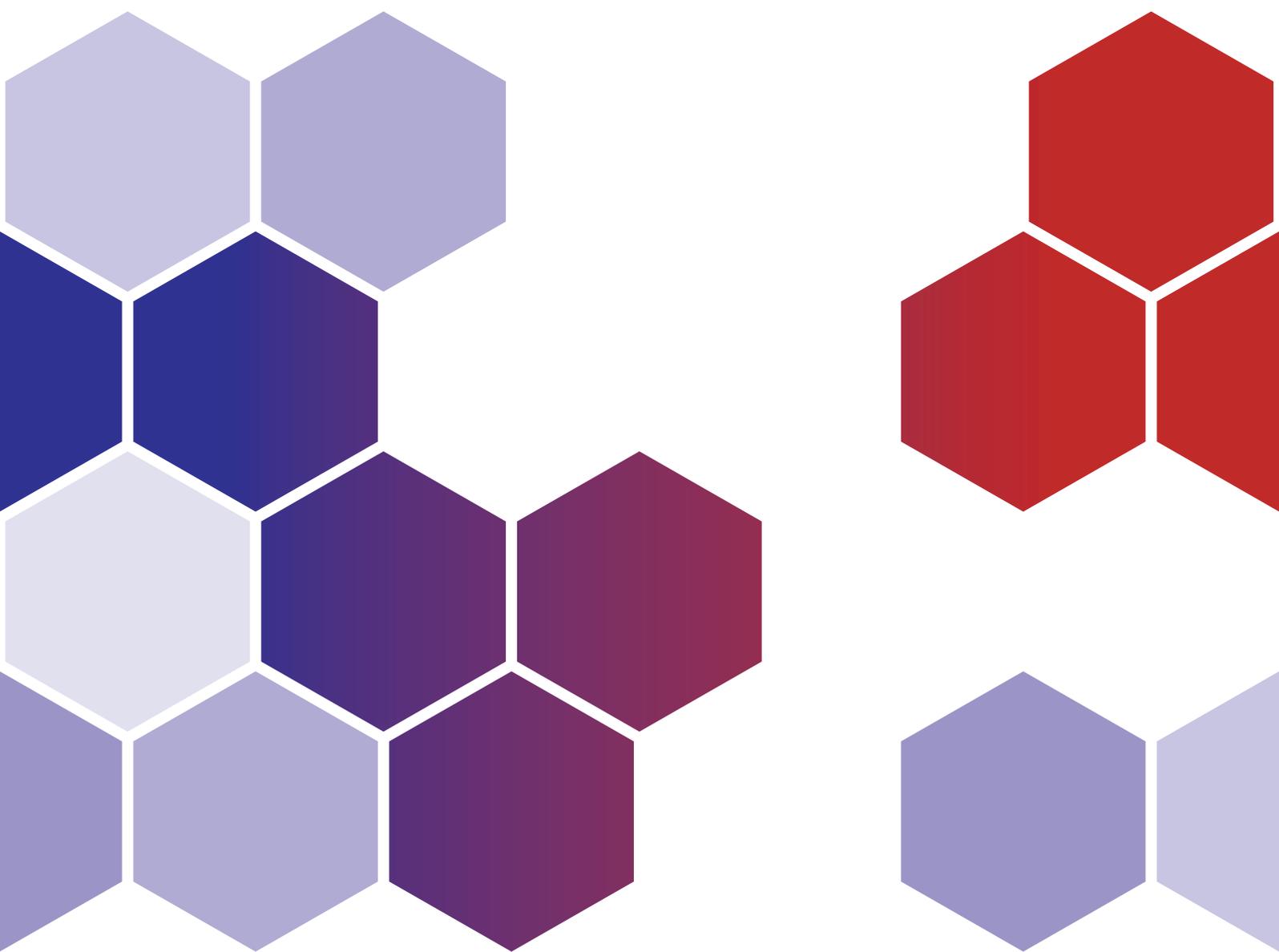
Consideration must also be given to the concreting stage when drilling with water. As discussed in *Table 2*, water is a Newtonian fluid i.e. without any gel strength. Its low viscosity means it cannot hold sand and coarse silt particles in suspension for long and these can settle out during base cleaning, cage installation and concreting operations.

Depending on the ground conditions clay particles may become dispersed into the drilling water. These particles will not settle rapidly in the drilling water column and they can help promote filter cake formation. In addition the clay particles increase the drilling water viscosity, which also slows down the settlement of coarse particles. These particles help the development of the interface layer during concreting.

For the reasons given above, it may be necessary to completely replace the drilling water with clean water at the end of excavation, or use sedimentation aids to enhance the settlement of fine particles.

Section 5

Execution



5.1 Mixing and Storage

General

An effective mixing system should activate all the raw material giving cost effectiveness in both raw material and mixing time. Efficient mixing is dependent on the initial contact between the raw material and the mixing water. Raw material slowly added to fast moving or agitated water mixes more thoroughly and readily than dumping bags of powder into large mixing drums which can result in large clumps of dry powder encased in a skin of partially hydrated product. Whilst additional product may be added after mixing to bolster the properties of the support fluid, it is far more efficient to get the correct mix ratio (concentration) during initial mixing rather than adding more product to previously prepared fluid. For polymer fluids, it is usually necessary to boost polymer concentration after each use and thus adding further polymer to used fluid is regular practice. A poorly dispersed/hydrated fluid never quite develops as good fluid properties as better-mixed fluids.

Support fluid preparation generally involves three stages:

- dispersion (initial wetting)
- hydration (with or without high shear mixing)
- homogenisation (unification of the entire volume by controlled circulation)

Bentonite

Bentonite fluid is normally prepared in a dedicated plant that includes a high shear mixer, hydration tanks and a fluid recirculation system. A bentonite fluid does not develop its

properties immediately on contact with water as the clay must swell so that clay sheets can separate and disperse. Some time for hydration should be allowed between mixing and use. The hydration time will depend on the type of bentonite and the level of shear in the mixer. As bentonite fluid must be allowed to hydrate for some hours before use (often 4 - 24 hours), hydration tanks are an important feature of bentonite use.

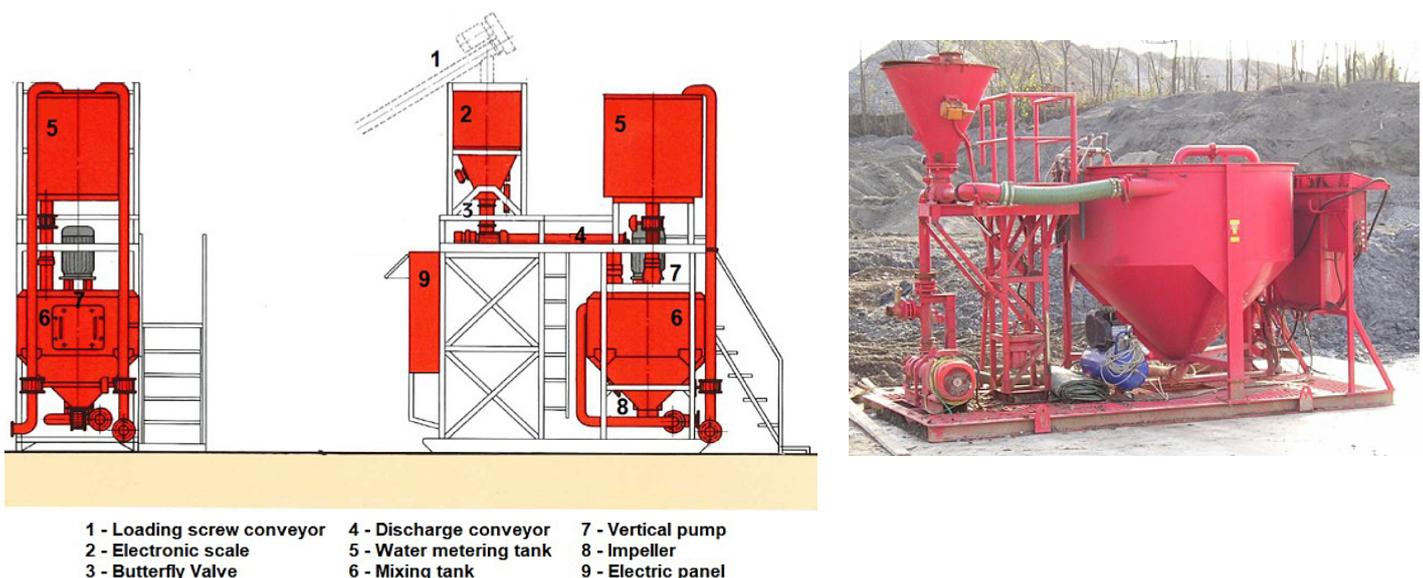
The key parameters to be considered when mixing a bentonite fluid include:

- water quality (pH, dissolved salts)
- mixing time (this has an impact on the clay particle dispersion affecting initial hydration and development of properties)
- shearing energy (to ensure particle dispersion)
- fluid circulation in storage (especially at the early hydration stage)

There are many designs of high shear mixers available most of which incorporate the same basic principle of a high shear mix head which also acts as a centrifugal circulation pump linked to a mixing drum. Typically, when the fluid in the drum has been mixed for the required time, the pump sends the mixed fluid to the hydration tank(s).

The difference in the numerous mixers available is the complexity of the feeds into the drum (water and powder). A semi-automatic mixer feeding powder from a silo and incorporating water measurement above the drum is shown in *Figure 25*. The mixing drum may also incorporate rotating paddles.

FIGURE 25 SCHEMATIC AND PHOTO OF A HIGH SHEAR MIXER



Whilst most bentonite fluids are mixed using high shear mixers, other methods may be used and these are described in the Polymer section below.

Polymer

Mixing of polymer fluids typically utilises a greater variety of mixers than for bentonite fluids. Inappropriate mixing techniques can lead to problems including agglomerate formation, and the possibility with liquid polymers of solvent emissions. Simple stirring of solid-liquid mixtures cannot guarantee prevention of quality deviations between mix batches or waste of raw materials. Given the wide range of polymer types available, the supplier should specify which types of mixing equipment are suitable for their product.

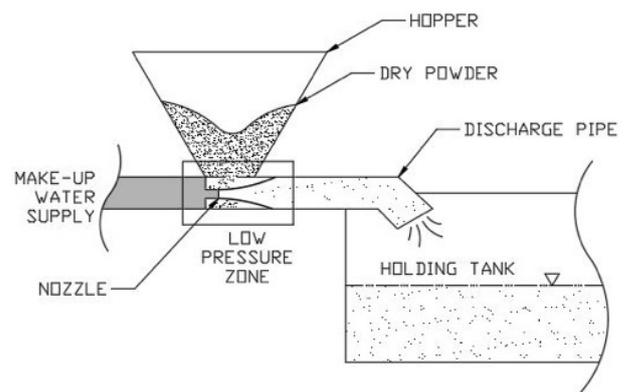
The simplest approach to wetting fine powder is to gravity feed/pour the powder slowly into a stream of water exiting a hose. If the stream is passed over a flat plate (called a splash plate), the surface area of the wetting stream is increased. The user should carefully sprinkle the powder onto the plate avoiding any build-up of material. Alternatively, the user can sprinkle the powder into the fan of water that forms off the edge of the plate. These methods are not conducive to dosing large volumes of powder (i.e. they are not suitable for bentonite but can be used for polymers which require around 1/50th the amount of dry material as bentonite fluids). *Figure 26* shows both methods: pouring powder directly into a hose discharge and make-up water flowing across a plate while the user introduces polymer powder.

FIGURE 26 GRAVITY FEEDING POLYMER INTO A STREAM OF RECIRCULATED POLYMER FLUID



For large volumes of fluid, a venturi hopper may be preferred (also called hopper eductor, venturi eductor or mud gun). These devices vary from crude to very sophisticated. The most rudimentary versions have only a reduction in the supply line cross section (a nozzle) that substantially increases the water velocity and thereby creates a low pressure zone in the air around the nozzle. The nozzle is incorporated into the base of a hopper (funnel) in which the dry powder is introduced and the low pressure pulls powder into the stream as it exits. The discharge pipe around the nozzle stream provides a corridor for some initial mixing along with the initial wetting as the fluid discharges. *Figure 27* shows the features of a venturi hopper.

FIGURE 27 A SIMPLE VENTURI HOPPER ASSEMBLY: 50MM [2 IN] SUPPLY LINE REDUCED TO 19MM [3/4 IN] TO FORM NOZZLE (TOP); HOPPER WITH NOZZLE PORT AT THE BASE (MIDDLE); AND SCHEMATIC OF SIMPLE VENTURI HOPPER MIXING SYSTEM (BOTTOM)



Methods to regulate the dry powder flow rate into the nozzle stream are preferred such that the powder flow rate is suitable for the water flow rate. This can be manually fed, controlled by valve or slide gate at the base of the hopper (Figure 25, butterfly valve), or an Archimedes-screw feeding system can be used (Figure 28). Figure 28 shows a user carefully filling the hopper to prevent overflowing/overfeeding the nozzle. If users are not careful, there can be clogging at the base of the hopper (Figure 29) and ineffective initial wetting where clumps of unmixed powder are pulled into and pushed out of the discharge pipe so producing 'fish-eyes' which may never fully dissolve.

FIGURE 28 VENTURI HOPPER SYSTEM MANUALLY FED (TOP); SLIDE GATE (MIDDLE); SCREW FEED (BOTTOM)

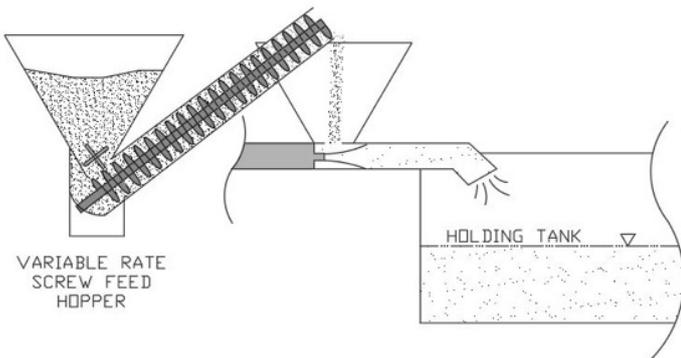
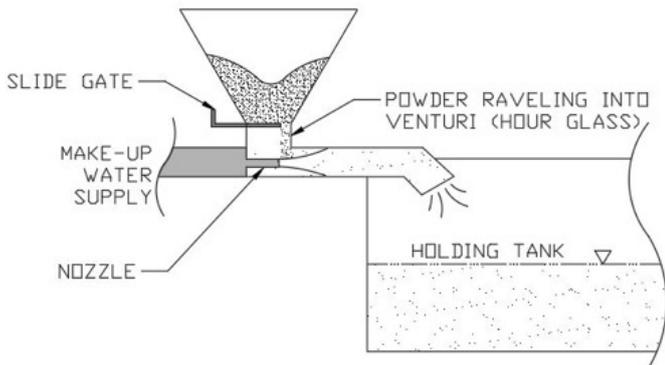


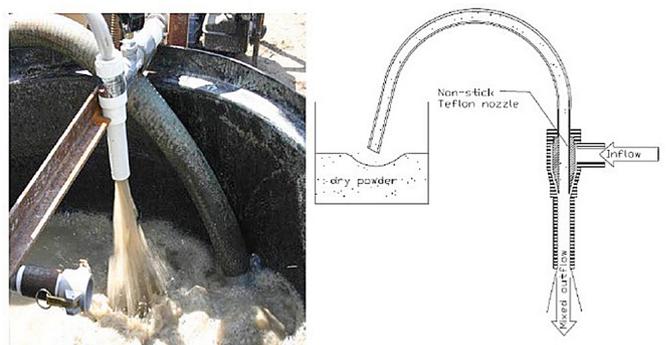
FIGURE 29 HOPPER CLOGGED WITH WETTED POLYMER (LEFT); BUILD-UP OF PARTIALLY WETTED MINERAL PRODUCT (RIGHT)



Typical venturi hoppers use 50 to 75mm [2 to 3in] supply lines but larger systems are available with lines up to 150mm [6in] in diameter with reduced sections (nozzle diameters of 100mm [4in]). In reality, the larger lines produce larger clumps of material that are then even harder to convert to usable support fluid. While it is tempting to scale-up systems with larger lines and hoppers when larger volumes are needed, using smaller hopper eductor units for longer times tends to be more effective and prepares the fluid more quickly.

Vacuum eductor mixing systems are a subset of the venturi type systems as they both make use of Bernoulli's venturi principle. However, these devices have significant differences from eductor hoppers: (1) in a venturi hopper, powder falls into a wetted chamber around the water jet which immediately promotes build-up and blocking; for vacuum eductors, the dry powder is pulled into the centre of an annular water column and never touches a wetted device surface so minimising build-up and clogging. Therefore, the powder is completely surrounded by water. (2) Powder material is introduced in proportional to the flow rate of the make-up water via vacuum feed and is not dependent on gravity fall (ravelling hour-glass effects), and (3) the interface orifice is made from non-stick Teflon to further reduce build-up anywhere in the device. Figure 30 shows a vacuum eductor wetting system with vacuum hose that pulls powder into the flowing water.

FIGURE 30 VACUUM EDUCTOR WETTING/MIXING BENTONITE POWDER (LEFT); INTERNAL SCHEMATIC (RIGHT)



Like the venturi hoppers, larger diameter units are not necessarily better as the wetting surface area does not increase proportionally to the increase in volume of dry powder. These units are suitable for parallel operation where the desired mixing flow rate of the make-up water can be used to tailor the correct number of side-by-side units.

Dry polymers require careful initial wetting and longer times to hydrate (typically 30 to 60 minutes) than liquid polymers. Liquid polymers can require longer initial mixing to achieve homogeneity during dilution but much shorter times to hydrate. It follows that mixer type and homogenisation procedure should be matched to the polymer type.

Where possible, homogenization and recirculation of synthetic polymer support fluids should avoid centrifugal type pumps where the fluid experiences high shear. Alternate recirculation methods such as air bubblers or diaphragm pumps are preferred. Tanks with sloped bottoms tend to be more effective in recirculating without having stagnant portions of the tank.

Cellulose based natural polymers (CMC, PAC), do not suffer the same damage as synthetic polymers and high shear mixers and centrifugal recirculation pumps can be used.

Storage

Storage equipment is used to store the support fluid whilst developing its properties or in readiness for use or re-use. There are many types available that are suitable to store all fluid types, including:

- square/rectangular tanks
- circular tanks
- inflatable tanks
- vertical silos
- modified containers
- gunited ground pits (not for synthetic polymers)
- ground pits with lining
- the pile/panel under construction

Shape and geometry may be criteria for selection depending on the area available on site for fluid storage. The storage capacity required will depend on the volume of the individual foundation elements and the method and speed of construction, and is therefore site specific.

Storage tanks for mineral fluid should incorporate moving paddles or agitators in the holding/storage tanks to control sedimentation of mineral products that are suspended and not dissolved (like synthetic polymers). Additionally, sloped tank bottoms are preferred to direct sediment material to the recirculation pump pick-up location. This can be as simple as blocking up the tank on one side. *Figure 32* shows storage tanks that would

incorporate tank bottom agitation systems. *Figure 33* shows silo type, funnel bottom vessels that prevent stagnant sedimentation inherent to flat bottom tanks without agitation systems.

Storage tanks for polymer support fluid can incorporate bubbler pipes attached to the bottom of the tank to maintain homogenous fluid. Recirculation pumps (if used) should be low energy such as diaphragm type pumps. Polymer storage tanks also benefit from sloped tank bottoms or inclined tanks to promote discharge to supply lines.

FIGURE 31 RECTANGULAR STORAGE TANKS



FIGURE 32 VERTICAL SILO STORAGE TANKS



5.2 Pumping

General

Pumps are used for transferring fluids or keeping them in motion as a means of agitation or continued mixing. Commonly used pumps are centrifugal or positive displacement (PD). Further detail including characteristics and advantages/disadvantages of each type is given in *Appendix C*.

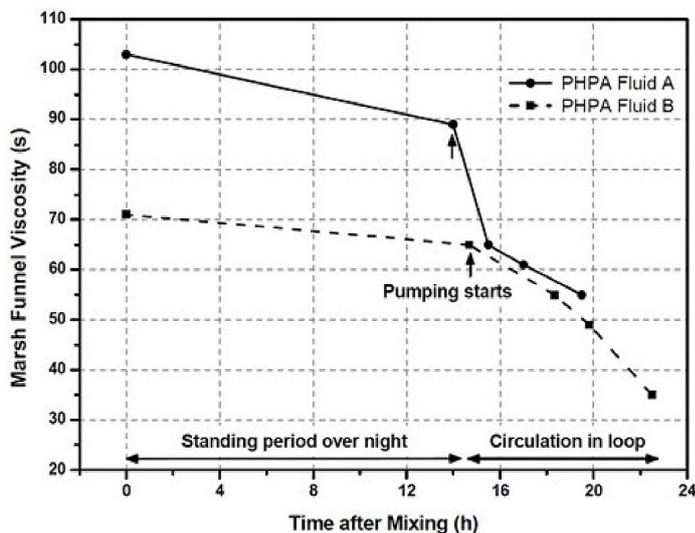
Bentonite fluids are typically transferred between mixer, storage, pile/panel and separation plant by centrifugal pumps (both surface mounted and submersible). Pumps may be left running recirculating the fluid when delivery is not required.

For high molecular weight synthetic polymer fluids, fluid shear should be minimised and recirculation avoided. Lam et al (Lam et al, 2010) report the results of an investigation into the effects of continued shear on the properties of polymer fluids and showed that there was significant degradation of the polymer fluid properties as a result of continuous circulation through a centrifugal pump (see *Figure 34*).

The investigation was carried out on-site using a typical bentonite fluid pipework configuration. The centrifugal pump was run continuously, as is the normal practice for bentonite fluids, and the fluid was circulated back to the storage tank when the valve in the feed line to the excavation was closed so that the pump need not be repeatedly turned on and off during the excavation. This is an important aspect of plant operation as the storage tank may be at some distance from the excavation. Continuous circulation, although wasteful of energy, is generally regarded as beneficial for bentonite fluids as it prevents settlement and improves hydration.

From *Figure 34*, it can be seen that for the PHPA polymer fluids, once pumping started the Marsh funnel time for each fluid dropped and continued to do so up to the end of the test. Both PHPAs were of high-molecular weight (i.e. they were long-chain molecules - longer chain lengths tend to give higher viscosities) and it seems that the chains were being broken as a result of continuing shear in the centrifugal pump and pipework so reducing the fluid viscosity. The damage was so severe for Fluid B that the initial 65 Marsh time (after overnight ageing) had reduced to 35 s at 22.5 h (after approximately 8 h recirculation) and was tending to that of pure water (28 s for 1 litre discharge and 26 s for 1 qt).

FIGURE 33 REDUCTION IN VISCOSITY OF PHPA POLYMER FLUIDS DUE TO RECIRCULATION



To avoid viscosity reduction due to prolonged shear in centrifugal pumps, it is recommended that diaphragm pumps are used for PHPA fluid transfers as they induce less shear and can be designed to stop automatically (so also saving energy) when the pressure rises as a result of closure of the delivery valve. If diaphragm pumps are not available, fluid recirculation should be minimized (Jefferis & Lam, 2013).

Centrifugal pumps are usually used to remove polymer fluids from excavations during concreting as flow rates are high and pumps which can be immersed in the fluid (submersibles) are often used.

Fluid Transfer and Supply Pumps

When selecting the pump to supply support fluid to an excavation it is necessary to consider the excavation rate per hour in the given soil conditions. As a general rule the deeper the excavation the slower the progress will be. Thus the initial 10 to 20 m [30 to 60 ft] of excavation is normally much faster. The harder and more compact the soil and/or the larger the cross-section of the excavation, the slower the excavation rate. A further consideration for pump selection is the head capacity necessary to achieve the full design flow rate to the most remote areas of the site and to overcome any static lift requirement (e.g. if the pump is located at a lower level than the excavation). The pump capacity is normally chosen so as not to sacrifice production and must be matched to the highest expected excavation rate.

In general, when using direct circulation methods (e.g. buckets, augers and grabs), the rate of supply only has to replace the volume of the material excavated. With reverse circulation systems (e.g. hydromills and pile top drill rigs) the

cuttings are removed by pumping the fluid containing the cuttings from the base of the excavation. The required pumping rates are therefore much higher than those required with direct circulation methods.

Typical supply pumps have capacities in the range 100 to 150 m³/hr [400 to 650 gpm]. This is generally sufficient for direct circulation methods. For reverse circulation, higher supply pump capacity is required often in the range of 200 to 300 m³/hr [900 to 1,300 gpm].

Fluid Retrieval Pumps

Except when initiating the pour, the flow capacity of the retrieval pump is governed by the rate of concrete pouring (typically not more than 80 m³/hr [100cy/hr]), and its head capacity is governed by the distance the fluid has to be pumped plus any static lift. A variable flow rate pump may be a great advantage in order to match the fluid recovery rate with the rate of concrete pouring. Submersible centrifugal pumps are a typical choice. Positive displacement pumps (e.g. large duplex diaphragm pumps) may also be used. A positive displacement pump makes a fluid move by trapping a fixed amount and forcing (displacing) that trapped volume into the discharge pipe. *Table C1 in Appendix C* lists the different types of positive displacement pump.

The initial concrete discharge rate is generally that which determines the pump flow rate. Tremie pour initiation requires a fixed volume of concrete to be poured without interruption to ensure the integrity of the element. The larger the section to be poured, the larger the pump required to match the maximum concrete discharge rate. This will be greatest when multiple tremie pipes are used. This is covered in detail in the EFC/DFI Tremie Concrete Guide, *Section 6.5*.

5.3 Excavation and Cleaning

The main purpose of any support fluid during excavation is the stabilization of the excavation (see *Section 2.4*). Diaphragm wall panels have a greater need for stability during excavation than bored piles due to their rectangular shape which reduces the ability of arching in the surrounding soil due to the increased stress levels at the corners. Some polymer fluids may not be able to adequately support such rectangular excavations but are able to support large diameter circular excavations in the same soils.

Dry or loose sand layers will easily absorb mineral fluids with low density until a sufficient filter cake has been created which will then reduce the fluid loss and stabilize the excavation. The ability of some support fluids to clog large pore spaces (gravel layers) may be important to achieve excavation stability. Large foundation elements may have to be excavated slower than possible to allow for the support fluid to work properly. Depending on which soil or rock type is excavated, the support

fluid also must prevent the deterioration or softening of the native material when it comes in contact with the fluid. Some shale materials are very sensitive to drilling with water, but less affected by mineral and polymer fluid.

Most support fluids will also change their properties as excavation progresses as they get charged with fines from the native soils. Monitoring these changes during excavation (especially for large and deep elements) and adjusting the fluid accordingly is required to maintain the stability of the element and minimize the impact of filter cake build up. It will also help with required cleaning or fluid exchange procedures before concrete is placed.

In addition to their main requirement of stabilising the excavation, support fluids also have to provide several characteristics specific to the various excavation techniques.

Table 6 highlights some key requirements.

TABLE 6 TYPICAL EXCAVATION METHODS WITH SUPPORT FLUID REQUIREMENTS

Excavation method	Requirement for Support Fluid
Auger	Bind the material sufficiently, so that it does not 'slide' off the auger
Bucket / Grab	Allow sedimentation, so that most solids are contained at bottom of excavation and not distributed throughout the entire excavation
RCD/Hydromill	Aid suspension of solids during transport to surface/separation plant
Percussion Drilling	Lubricate hammers
Dredging / Airlift	Maintain low viscosity, so that the excavation pipe is not plugged

If temporary or permanent full depth casing ahead of the excavation is used, the purpose of the fluid is less to support the excavation but rather counteract groundwater pressure. As casing is installed concurrent or behind the excavation, the support fluid will still have to ensure the stability of the excavation (even only for a short section ahead of the casing).

The cleaning of the support fluid during excavation with conventional tools (augers/buckets/grabs) is normally left to the end of the excavation process to avoid interruptions. Nevertheless, the process can already start as the excavation progresses. For most polymers and some polymer-bentonite blends, the addition of flocculants aids the process of cleaning by settling most of the fines to the bottom section of the excavation, where they can be picked up with each bite of the tool.

Careful dosage of flocculants and appropriate mixing into the support fluid is essential.

When using reverse circulation methods for excavation, the cleaning of the fluid takes place during excavation, since fluids are circulated to the surface and can be cleaned before they re-enter the excavation. The various cleaning or separating methods are described in *Section 5.5*.

Typical base cleaning methods include the use of cleaning buckets, which do not have teeth and are properly sealed so that they can 'scoop up' fines and soft debris from the very bottom of the excavation, large and powerful submersible pumps, and airlift devices or suction pumps which can connect to the tremie pipe. Gravity sedimentation inside the excavation (sometimes over-night) or the use of flocculants can again aid the cleaning process and reduce the time required to settle out most fines. It is important that these flocculating agents are uniformly mixed into the pile or panel otherwise they can lead to formation of a sticky sludge at the base. This sludge has been found to be difficult to remove from the base of the excavation. This can contribute to inclusions during the concreting phase. If required, the entire support fluid may have to be exchanged to avoid excessive sedimentation of suspended fines.

For reverse circulation methods the tool is simply kept in the excavation and fluid is pumped to the surface until sufficient cleanliness is achieved. Fresh and/or recycled support fluid is pumped into the excavation.

Where items such as stop-ends or reinforcement cages are to be inserted, cleaning should be carried out before insertion.

The time elapsing between the final cleaning of the excavation and the commencement of concreting should be kept as short as practical. When large and very deep elements are installed which derive their main load bearing capacity from end bearing and therefore require a very clean support fluid at the base of the excavation, additional cleaning procedures may be required after the rebar cage is installed. These typically involve airlifting or suction pumps operated through the tremie pipe.

Adequate base cleaning is essential to ensure good base resistance, regardless of whether mineral or polymer support fluids are used. The end bearing capacity of piles and diaphragm wall panels is affected by the presence of debris and support fluid left behind as part of the construction process. Appropriate levels of base cleanliness should be discussed and agreed at the project design stage and verified accordingly on site. A range of methods for checking base cleanliness is available and some examples are provided in FHWA GEC #10, and in ICE SPERWALL see EFFC/DFI Tremie Concrete Guide *Section 6.2*).

There are a number of commercially available products available to assess base cleanliness. A number of these will be trialled on site during the Field Research Study (see

Section 1.3) with the intention of assessing their practicality and accuracy. The results, including any recommendations, will be presented in Edition 2.

5.4 Reactions with the Ground

The performance of support fluids is degraded by the excavation process, especially if the fluid is used repeatedly during a project due to the dispersion of fine grained material into the fluid. There will also be some dilution and possible contamination of the fluid by the groundwater associated with the soil dispersed in the fluid. Appropriate monitoring during excavation therefore requires measurement of fluid density, viscosity and sand content on samples from the trench - values of all these parameters will increase with the dispersion of soil into the fluid. The effect of the solids charge happens mainly with mineral fluids because their gel can keep particles up to a certain diameter in suspension whilst they will slowly settle in a polymer.

Inevitably there will be some loss of the support fluid with excavated soil and to the adjacent ground by bulk penetration/filter effects. There must therefore be a constant supply of fresh make-up fluid which will partially offset the degradation of fluid properties as discussed above.

Physical Loading

High rates of production are achieved when the fluid viscosity is maintained within in a reasonable range. In cohesive soils with high clay or silt content, the introduction of suspended fines increases the viscosity and the specific weight of the fluid. Heavy fluid slows down the tool in the hole and reduces the contact pressure on the teeth. Excessive solids content increases the filter cake thickness which may impact the up and down movement of the tool. Loaded fluid is a cause of wear for pins, sheave bearings, telescopic kellys and wire ropes.

The physical loading by sand is easier to measure with the sand content test, and manageable with the separation equipment in case of mineral fluids and with settlement basins where polymer fluids are used.

Some polymer fluids have the advantage of carrying little suspended solids or limiting the swelling capacity of soil clays and are therefore beneficial from an equipment wear standpoint. Good lubrication of the tool surfaces facilitates the travel of the tool in the hole as well as the discharge from the bucket or auger with no loss of time due to stickiness in clayey soils as may be found with mineral fluids. The polymer can however sorb onto soil particles thereby reducing the active polymer concentration. It is well recognized that

polymer concentration must be boosted after each use of PHPA fluids. Ongoing fluid testing allows decisions on the need for addition of fresh polymer, use of adjuster additives or a total replacement of the used polymer with fresh before the concrete pour.

Polymer clay blend fluids offer the same advantages as pure polymer fluids regarding physical loading. Low viscosity of the fresh fluid can be a good solution to mitigate the loading effect and control the drift of properties.

The primary method to reduce physical loading is solids control equipment as detailed in *Section 5.5*.

Chemical Reactions

Support fluids can be adversely affected by chemicals in the ground or groundwater (as shown in *Table 7*) but in practice the effects are often quite modest provided reasonable precautions and working practices are adopted. Chemical species commonly encountered include:

- cement from concreting or pre-grouting of open formations
- sea water where effects of ionic strength and calcium and magnesium may be an issue
- more rarely gypsum and evaporites may be encountered
- volatile organic compounds (VOC's), hydrocarbons, heavy metals, solvents and acid or alkaline solutions

Chemical adjusters can be added to the system to offset some of the effects of the contaminants. These include alkali hydroxides and sodium carbonate (water treatment), sodium bicarbonate (cement contamination), dispersant or adding sacrificial raw material to the system to maintain its behaviour. Typical treatments are shown in *Table 8*.

In extreme cases, it may be necessary to change the type of support fluid.

TABLE 7 INFLUENCE OF PHYSICAL LOADING AND CHEMICAL POLLUTANTS ON THE SUPPORT FLUID CHARACTERISTICS (S=SYSTEMATIC EFFECT; P=POSSIBLE EFFECT)

	Physical loading	Chemical reactions
Viscosity	P	P
Density	S	
Filtrate fluid loss	P	P
Filter cake thickness	S	P
pH		P
Sand content	S	
Pollutant	Sand, silt, clay	pH (peat, grouted soil, concrete), salts, gypsum, sea water
TREATMENT (pre or post treatment)	Low molecular weight polyacrylate (clay/silt) Desanding Desilting Fresh fluid	Sodium carbonate Sodium bicarbonate Polymer CMC Low molecular weight polyacrylate

TABLE 8 COMMONLY USED TREATMENTS FOR MINERAL FLUIDS

Type of soil or pollutant	Effects on mineral fluid	Possible treatments				
		CHEMICAL ADJUSTERS				
		Sodium carbonate	Sodium bicarbonate	Dispersant	Cellulosic polymers	
Fine soils (clay, silt, marl)	Viscosity			✓		
	Density					✓
Chalk	Viscosity			✓		
	Density					✓
Gypsum (pollution difficult to control)	Viscosity	✓		✓		
	Filtration				✓	
Organic matter (lignite, peat, organic mud,...)	Viscosity				✓	
	Filtration	✓				
	pH	✓				
Cement	Viscosity		✓	✓		
	Filtration		✓			
	pH		✓			
Water table dilution	Viscosity (*)					
	Filtration				✓	
Sea water or Brine	Viscosity	✓				
	Filtration	✓			✓	
	pH					

(*) : Mainly in sandy gravel layers with high groundwater levels.

The period between support fluid cleaning and concreting should be as short as possible to limit the filter cake growth.

Loss of Support Fluid

The support fluid level can sometimes drop suddenly or continuously, during or after excavation. This can be due to the interception of underground cracks, karsts, voids, galleries etc. and induce a risk of trench collapse.

EN 1538 Clause 8.4.3 states that “When a sudden and significant loss of the support fluid occurs during excavation, the excavation shall be refilled immediately with an additional volume of support fluid, possibly containing sealing materials”. The site installation must allow for stockpiling sufficiently large amounts of replacement fluid for this purpose.

Loss of support fluid may require additional measures depending on the importance of the fluid loss in the ground

and the characteristics of the ground. Where the Site Investigation identifies a risk of fluid loss, a pre-grouting operation is one option to prevent fluid loss during the project.

A variety of materials called “lost circulation materials” can be also be used to help reduce lost circulation of fluid. They may be divided into four categories:

- fibrous materials (mineral or organic) such as slag fibres and cellulose fibres
- flakes such as corn flakes, mica flakes and shredded wood chips
- granular materials such as gravel, sand, mineral fillers, nutshells, soil and crosslinked polyacrylamide (water swellable but non-soluble polymers)
- viscosity modifying additives such as highly concentrated polyanionic cellulose , the idea being to locally increase the viscosity of the fluid to form a semi-solid mass and plug the voids causing the loss into the surrounding soil.

When a significant sudden loss is experienced, backfilling the excavation with granular soil treated with cement or low strength backfill material (e.g. leanmix concrete) is a common practice.

Different approaches are possible to prevent or reduce the fluid loss in the soil. It is important to ensure that the selected support fluid will not be adversely affected by the methodology implemented. For example, when using pre-grouting and backfilling with cement treated materials, it is important to ensure that the support fluid contamination can be controlled.

5.5 Treatment and Recycling

Bentonite, Natural Polymer and Modified Natural Polymer

Section 5.4 details the chemical reactions and the chemical adjusters which can be used to restore the support fluid's properties. In the case of physical loading, mechanical equipment can help to remove the soil particles from the support fluid.

A wide range of separation equipment is available. The types of equipment commonly used are given in Table 9.

TABLE 9 TYPICAL D₅₀ CUT POINTS FOR SEPARATION EQUIPMENT

Equipment Type	Typical D ₅₀ Cut Point	Typical Maximum Capacity
Primary Shaker Screens	<3 mm	1,000 m ³ /hr
Secondary Shaker Screens	0.2 mm to 0.4 mm	500 m ³ /hr
Desander cyclones	80 µm	250 m ³ /hr
Desilter cyclones	20 µm	150 m ³ /hr
Centrifuges	>5 µm	25 m ³ /hr
Filter Presses	>5 µm	25 m ³ /hr

The efficiency of all types of separation plant decreases significantly with increasing fluid density. It is therefore important to characterise the material being excavated and estimate the type and quantity of material that will need to be removed from the support fluid in order to assess the separation equipment required.

With reverse circulation methods, the separation plant may become the critical factor determining productivity, especially in weaker and/or finer strata. Hydromills must be limited to a rate of advance which does not overload the fluid.

Under 20-30 µm, it is almost impossible to remove particles without degrading the support fluid. Centrifuges and filter presses are therefore often used to treat fluid before disposal or to control fluid density when using hydromills.

Schematics related to equipment and particle size are shown in Figures 35, 36 and 37.

FIGURE 34 MECHANICAL SEPARATION PLANT RANGES

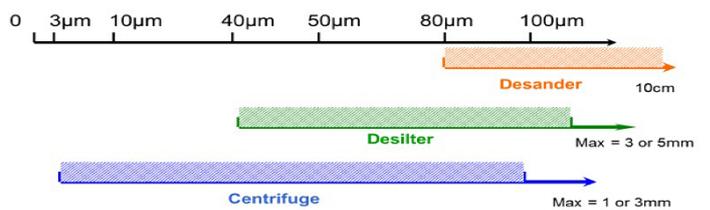


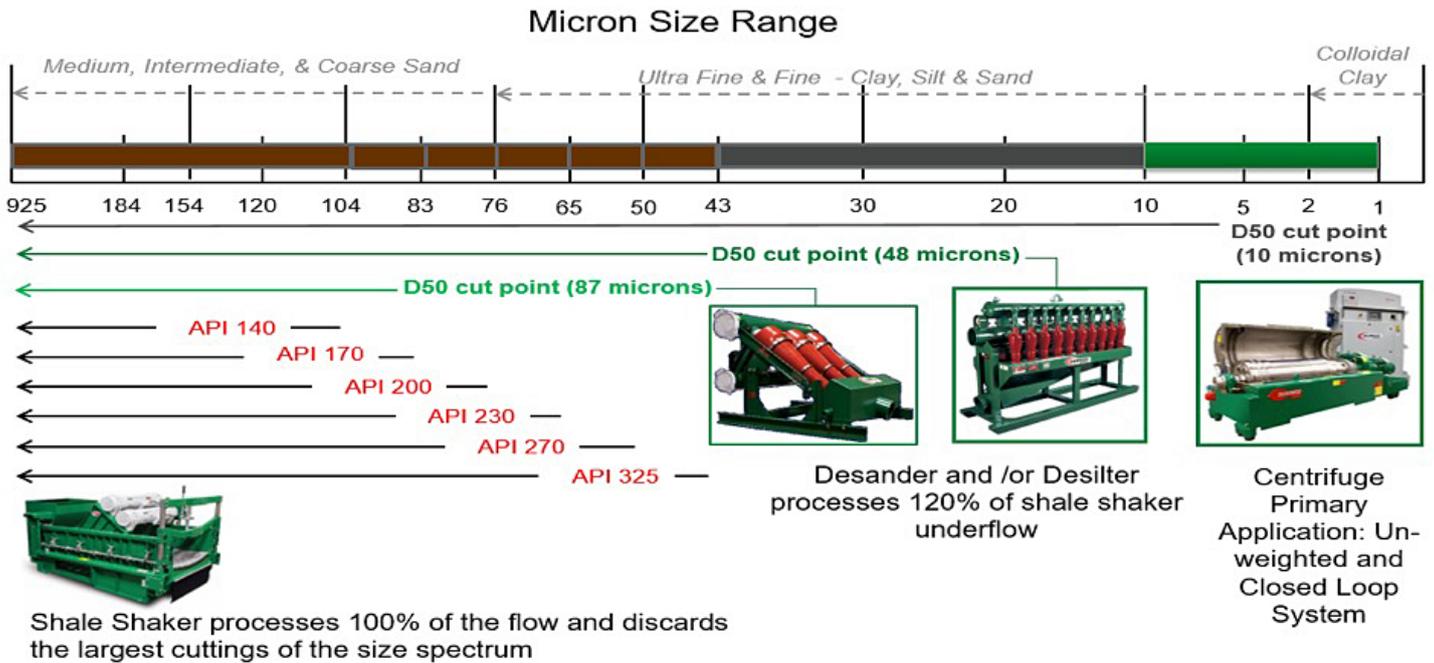
FIGURE 35 EXAMPLES OF DESANDER CYCLONES (TOP LEFT), DESILTER CYCLONES (TOP RIGHT) AND CENTRIFUGE (BOTTOM).



FIGURE 36 SOLIDS CONTROL EQUIPMENT APPROPRIATE FOR EACH PARTICLE SIZE

Solids Control Equipment

Un-Weighted System



Synthetic Polymer (PHPA)

PHPA polymer fluids do not tend to hold soils in suspension. Consequently, settlement of even fine-grained soils such as silt can occur after completion of the excavation if the fluid is not adequately cleaned. The separation plant used for cleaning bentonite is not suitable for polymer because the polymer tends to clog the screens, and the shearing action of the equipment tends to break down the polymer. The typical method for cleaning a polymer is to add flocculating agents to help drop suspended solids out of suspension and then provide time for the sediments in the fluid to settle out. It is sometimes necessary to fully exchange the drilling fluid with fresh fluid by pumping from the base of the excavation and discharge to holding tanks where the sedimentation can take place (see Figure 38).

FIGURE 37 SEDIMENTATION TANKS FOR PHPA POLYMER DRILLING FLUID



After completion of the work, the polymers can be broken down with a de-activating agent (bleach works for most types of polymers) causing the suspended solids to drop out quite easily. This property provides one of the attractions with polymer fluids in that disposal can often be accomplished with relatively little cost and effort compared to bentonite.

5.6 Concreting

Concreting operations are discussed in detail in *Section 6* of the EFFC/DFI Tremie Concrete Guide and this Section should be read in conjunction with that Section of the EFFC/DFI Tremie Concrete Guide.

Support Fluid Sedimentation

As shown in *Table 2*, silts and clays may be suspended in mineral fluids. This suspension is generally stable within the time frame from base cleaning to concreting and no separation will occur. Some sedimentation may occur on bars and ribs. However, coarse silts and sands may settle out within this time frame and therefore the excavation fluid may need to be exchanged with a fluid with low sand/solids content prior to concreting.

Polymer fluids loaded with silt may pose a risk of silt sedimentation onto the horizontal steel and the ribs of vertical bars and the base of the excavation with possible accumulation and fluid entrapment. In addition, the viscosity of the fluid loaded with sand may increase and this will slow the sand settlement rate. Flocculating agents are also used, which bring together the fine particles to form flocs.

The high calcium concentration and high pH of concrete will break down most polymers which assures that in most conditions there is no polymer left after a concrete pour. Any sediment that was present within the fluid will however remain in the excavation.

Initial Concrete Placement

When starting the concrete tremie pour, the support fluid and the concrete in the charged tremie pipe must be kept separate by a plug of material or by other suitable means (see *section 6.5* of the EFFC/DFI Tremie Concrete Guide).

Interface Layer

To ensure a distinct phase boundary between the displaced fluid and the concrete replacing it, the difference between the densities of these two materials should be maximised. This also promotes clean displacement of the support fluid from the rebar, avoids fluid inclusions in the concrete and so provides a good bond between steel and concrete. In normal operation, at the time of concreting mineral and polymer fluids will seldom have a density sufficient to raise concerns. It is only on rare occasions such as when using weighted support fluids to improve panel stability that the differential density may be an issue.

An interface layer can accumulate between the support fluid and the concrete. Based on limited information this layer can have a density up to 1,400 kg/m³ [90 lbs/ft³] with a relatively high viscosity. The layer therefore sits on top of the concrete but can affect the concreting operations as discussed in

Section 7.2 of this Guide.

The interface layer is thought to be formed from:

- when using bentonite, changes in the rheological properties of the fluid due to a chemical reaction between the fluid and the calcium ions from the concrete, or due to the flocculation of the bentonite particles in the presence of the calcium ions
- debris scoured from the pile base by the initial concrete placement which, having a low density, rises on top of the tremie concrete
- inadequate separation between fluid and concrete during initial charge leading to segregation of the concrete
- material from segregated concrete and concrete bleeding during the concrete placement. (cement and concrete fines are observed in the interface layer)
- material scoured by the concrete from the reinforcement ribs and horizontal bars and possibly from the filter cake
- material settling from the support fluid (if the concreting process is slow material from the support fluid can settle onto the interface layer)

At present there is very little site data on the properties of this interface layer material and the Task Group Members have developed field test methods to assess the interface layer properties. These properties could be incorporated into future numerical modelling studies.

CIRIA PG3 ^(Fleming & Sliwinshi, 1977) paragraph 4.2 identifies the importance of the difference between support fluid yield stress and concrete yield stress during support fluid displacement by concrete. The rheological profile of the fluid should be investigated, especially for bentonite support fluid. High gel strength bentonite could lead to some difficulties during the concreting operation.

5.7 Spillage and Disposal

All support fluids must be handled carefully and not allowed to flow untreated into the ground or surface waters during the entire process from mixing to disposal. This generally requires the use of a closed loop system to minimize the spillage potential. Typically, for mineral fluids 33 to 50% of the fluid will be lost during excavation or with the excavated soil. As a matter of course, significant loss occurs to the ground and most of this is beyond the control of the contractor.

Containment measures such as surface casings, trenches and barriers can be used to minimize the consequences of spillages during the excavation process when the grab, bucket or auger enters and exits the excavation. Minor amounts of fluid may be blown away by the wind and spill onto the adjacent ground or adhere to the excavated material. If the excavated material is not deposited directly into dump trucks, containment of the spoil pile is essential (*Figure 39*).

FIGURE 38 EXAMPLES OF CONTAINMENT MEASURES FOR A) TRENCH B) SPOIL C) CASING RESERVOIR D) BARGE



An example of good housekeeping practice to protect the surrounding environment is to install a containment barrier in combination with straw bales on the perimeter of the site. Stable working platforms above the working grade are essential for good fluid seepage control since fluid lines break or need to be opened and fluid should drain towards the excavation.

FIGURE 39 TYPICAL CONTAINMENT BARRIER



Additional containment measurements are required when working over water from barges or trestles.

Pumps are generally used to transport the support fluid into on-site containments tanks, silos or ponds. Such closed loop systems also help with continuous conditioning of the fluids and enable the re-use on site to minimize material and disposal cost.

Gravity flow directly from the excavation into an earth containment ponds is still used for some reverse circulation drilling methods in Asia. Since spillage risk is very high, such containment methods are not recommended.

FIGURE 40 EXAMPLES OF CONTAINMENT POND AND STORAGE TANKS



Despite the availability of effective recycling methods for all fluid types, some disposal of support fluids during or at the end of each project will be required. Strict disposal guidelines in Europe and the North America require careful management of fluid and solids disposal.

Disposal of liquid waste to landfill is banned or restricted in many countries. Some authorities require waste fluid to be transported to a waste water treatment plant whilst some allow the disposal of waste fluid into the sewer system or even in their storm water system. For all these options, the composition of the waste fluid must be identified in accordance with the requirement of the local authorities and/or sewer owners. Discharge permits typically require a chemical and physical analysis of actual waste fluid samples before the issue of permits. Since fluids will be a mixture of bentonite or polymer and excavated ground, composition is only known once excavation has commenced. As long as there is sufficient fluid storage available on site, the disposal permitting process has to start early enough to obtain all required permits.

The EU defines waste in their Waste Framework Directive (WFD) as "any substance or object which the holder discards or intends or is required to discard". The meaning of the word 'discard' under the WFD has a special meaning and is not necessarily the same as the dictionary meaning. The European Commission has provided guidance on the interpretation of key provisions of the Directive 2008/98/EC on waste.

In North America, wastes and their discharge onto landfills is regulated by the EPA Resource Conservation and Recovery Act (RCRA) 2014 manual. Local authorities may have additional requirements regarding waste disposal to landfill in areas for which they are responsible.

In general, all discharge permits will require the following:

- classification as to whether the waste is hazardous or non-hazardous
- the type of premises where the waste was produced
- the approximate quantity of waste
- the name of the substance or substances
- the process that produced the waste
- a chemical and physical analysis
- any special problems, requirements or knowledge related to the waste

The definition of hazardous waste is typically linked to the percentage of 'dangerous substances' and the associated 'hazardous properties' (i.e. metals or hydrocarbons).

Proper support fluid management leading to separation between solids from liquids is practical and economical. Depending of the type and composition of the fluid-soil mixture, adequate physiochemical treatment will greatly reduce the disposal quantities. Bentonite and polymer suppliers have developed product specific treatment methods. As a rule, minimizing the amount of disposal consists of separating the water from the solid ingredients and the following general treatment methods are available:

Polymer

- gravity sedimentation of suspended solids and removal as solid waste
- chemical breaking of fluid viscosity and settlement of suspended solids/fines with their removal as solid waste which may be added to the excavated soil
- chemical treatment of low solids fluid (bleach neutralization and pH adjustment) and discharge as waste water (after approval)
- mechanical treatment of broken polymer using centrifuge and/or filter press equipment separating fines from the water

Bentonite

- mixing fluid with cement and removal as solid waste after hydration
- mixing fluid with lime and dewatering through a filter press or a band (filter belt) press
- gravity sedimentation of suspended solids after flocculation and removal of sludge as solid waste or filling filtration bags (*Figures 42 and 43*)
- mechanical treatment using screening, centrifuge and decanting equipment releasing clear water and stackable solids (see *Section 5.5*), although this may also require chemical treatment

FIGURE 41 VERTICAL GRAVITY SILO/CLARIFIER

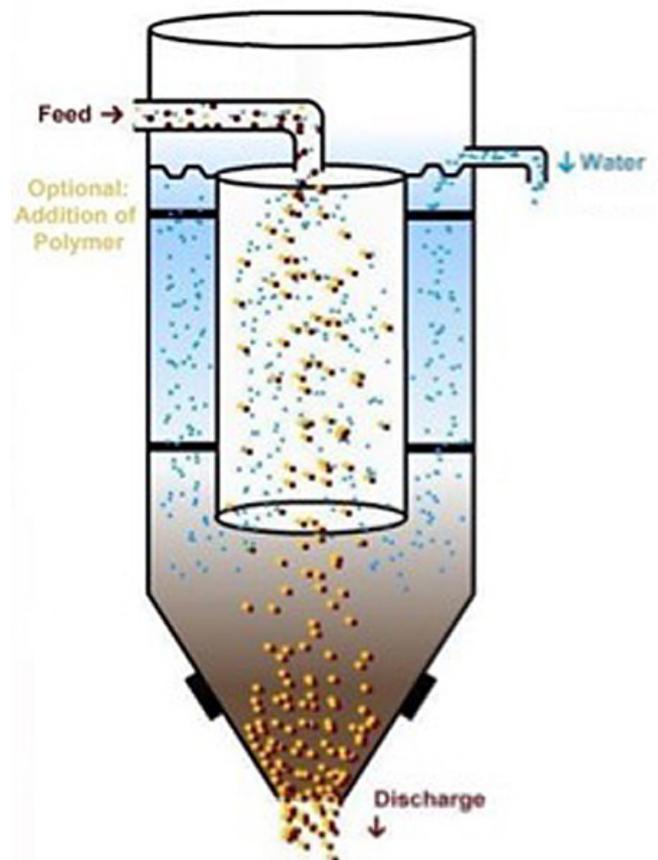


FIGURE 42 FILTRATION BAGS FOR PASSIVE SLUDGE DEWATERING

Some major misconceptions as to the hazardous nature of bentonite clay have caused undue expense for fluid disposal. While most polymer fluids can be sufficiently treated to be discharged as construction waste water, waste liquid bentonite (even after considerable treatment) is mostly classified as 'special waste' which typically requires disposal at special waste sites.

Very often bentonite is compared with fly ash as 'special waste', which has little scientific basis. Fly ash is an industrial byproduct often laden with heavy metals, whereas bentonite is a natural earth material. Bentonite can be detrimental to fish life in highly diluted and colloidal form in a natural body of water. There should be no objection to permit bentonite fluid ponds to desiccate and to use the resulting clay which is beneficial from an agricultural standpoint and welcomed by most farmers (note: chemical additives and pH need to be acceptable for used bentonite clay to be released in the environment). Dewatered waste bentonite fluid is easier to dispose of as a solid combined with general excavation materials.

If the excavated material is already contaminated, then there is the potential for the support fluid to also become contaminated. This will make recycling, treatment and disposal more expensive and complex.

5.8 Safety Considerations

Both bentonite and polymer support fluids have specific safety related issues that should be considered. The Material Safety Datasheet should identify most of those concerns. Both types of support fluids are eye irritants and require eye protection to be worn (especially during mixing). Eyewash stations must be made available with sufficient quantities of bottled eyewash solutions available to flush for 15 minutes. Each of these products also have respiratory considerations. In the US, OSHA recently reduced the permissible exposure limit (PEL) of crystalline silica to 50 micrograms per cubic meter of air. Although polymer is not currently regulated in the US, polymer workplace exposure in the UK is less than 4 micrograms per cubic meter respirable and 10 micrograms per cubic meter inhalable. Similar regulations for polymers are expected in the US in the future.

All support fluids can also contain admixtures that can cause severe reactions to employees exposed to them.

All support fluids can create a slip risk on platforms, ladders and work areas. This is especially the case with some polymer fluids.

Bentonite Powder

Bentonite is a respiratory irritant and during mixing operations employees should be fitted with half face masks with P-100 particulate filters or N-95 paper filtered masks. Bentonite does contain silica in low levels, which is considered a carcinogen. Bentonite contains less than 1 percent respirable crystalline silica (RCS) as determined by the Size-Weighted Respirable Fraction (SWERF) method. Bentonite would have to exceed 10 percent crystalline silica to be classified as hazardous. Bentonite does not have any significant skin contact related safety concerns.

The main admixtures used in bentonite fluids and associated safety considerations are summarized below.

Soda Ash

- Skin irritant (pH > 11)
- Not a respirable concern
- Emergency eye wash must be available

Bicarbonate of soda

- Emergency eye wash must be available
- 15 mg/m³ respirable dust

Sodium Acid Pyrophosphate (SAPP) - rarely used

- Irritating to the eyes, skin and respiratory system
- Respiratory protection is required
- Long sleeves, gloves and goggles are required

Polymer Powder

Polymer is a respiratory irritant and during mixing operations employees should be fitted with half face masks with P-100 particulate filters or N-95 paper filtered masks. Employees should also wear these respirators when adding polymer by the single bucket to increase the viscosity.

For a polymer fluid the maintenance of the high pH required for these solutions is a significant safety concern. The main polymer admixtures used to adjust the pH consist of hydrochloric (muriatic) acid to lower pH and 50 percent caustic liquids to increase pH. These two admixtures are delivered to the fluid mix manually by an employee typically dispensing the contents from 20 l [5 gall] liquid containers. This delivery method has several safety related issues that must be considered.

Direct exposure to the skin with either chemical causes severe chemical burns:

- safety showers/eyewash stations must be readily available
- a fifteen-minute dilution is required as a First Aid treatment
- impermeable clothing covering the body's trunk and extremities are required, chemical resistant gloves, chemical goggles, and face shield must be used when using these chemicals.

Additionally, safety considerations associated with excessive strenuous lifting of buckets to the mixing hopper of the mixing tank should be assessed.

Another admixture, sodium hypochlorite or bleach, can be used to break the polymer viscosity. This chemical is a skin irritant that can cause chemical burns and requires the same personal protective equipment as detailed above.

The requirement to have safety showers on job sites can be problematic. Many job sites are greenfield with no infrastructure to support safety showers. Portable eyewash/safety shower systems are available for purchase or to rent but they must be adequately maintained and are typically single use systems.

Some specific safety considerations associated with the use of safety showers on job sites include:

- what happens when there is a multiple exposure?
- when eyewash/safety shower is exhausted, how quickly can they be refreshed?
- the drilling operation must stop until they have been refreshed
- the water within the basin of the eyewash/safety shower must be kept tepid. They must not be in direct sun, which can be difficult to locate on a job site. In winter months the basin may freeze and potential hypothermia issues must be considered.

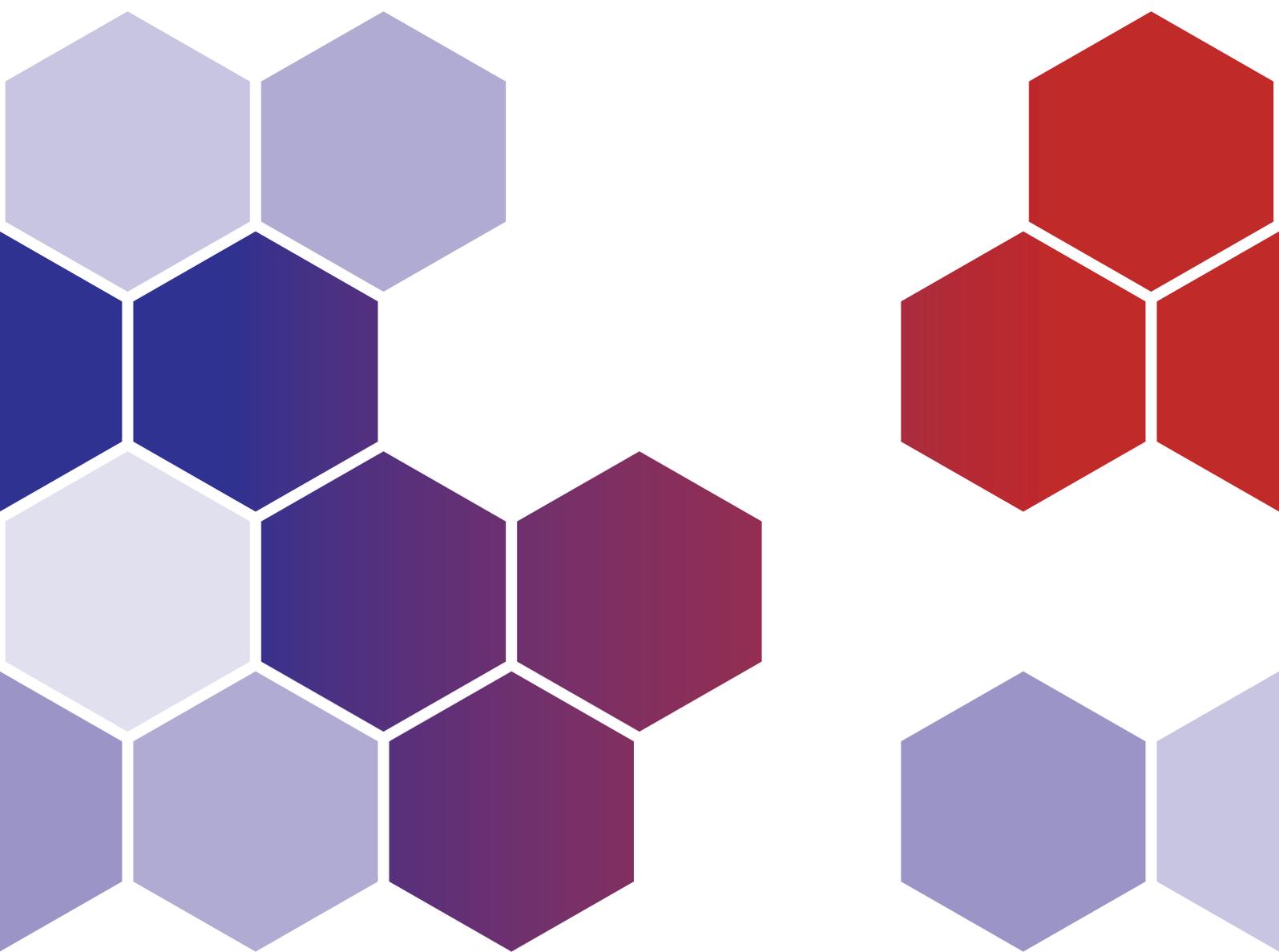
Summary

The health hazards during mixing and using support fluids are from inhalation of chemical agents and chemical spills. First Aid countermeasures must be available for any exposure that provide an immediate response to reduce the intensity of the hazard.

Communications of these hazards must be incorporated into the employer's HAZCOM/Health and Safety Policies, Supplier Datasheets. Supervisors should also be fully trained related to the safety risks. Logistics including First Aid countermeasures must be in place and convenient to an exposure location prior to engaging task activities that involve support fluid mixing and use.

Section 6

Full Scale Trials



An excellent way of obtaining important information on the construction aspects of any deep foundation element and thereby ensuring success of the works is to install one or more full-scale trial elements. Contract pile tests are also carried out as the work progresses. Examples include:

- trial pile load tests - to assess shaft resistance and base performance (see Section 5.3)
- excavations to expose completed panels and stop-end - to assess filter cake thickness and concrete imperfections (see EFFC/DFI Tremie Concrete Guide Appendix D)
- pile/panel verticality can be assessed. This is important for circular access shafts acting in hoop compression.
- trials can also be undertaken to assess the base cleaning, the initiation of tremie concreting and the development of the interface layer by recording density profiles. When the concreting is undertaken to the ground surface the interface layer can be sampled at ground level.

To get the most benefit, trial elements should be constructed using the same installation techniques, equipment and materials as proposed for the permanent works. Problems identified in full-scale trials can then be addressed before the permanent works are constructed. They also provide opportunities for refining aspects of the construction process and developing compliance parameters. The suitability and performance of the chosen support fluid will form only part of such a trial.

The extent and scope of the trial works should be proportional to the project size, complexity and risks. With specific reference to support fluids, the trial could investigate the following key areas:

A) Design - Temporary Works

- stability of the pile/panel during the excavation phase
- fluid loss from the panel/pile
- ground movements during pile/panel excavation

B) Design - Permanent Works

- filter cake extent and thickness, including its effect on concrete/soil interaction (may also require laboratory testing)
- reinforcement bond conditions

C) Quality Control

- stability of the support fluid and ground movements during excavation and concreting
- suitability of the support fluid sampling and testing regime
- confirmation of the support fluid conformity testing parameters
- suitability of the available water supply
- parameters of used support fluid for disposal purposes
- performance of the support fluid management setup, including quantity and quality of supply
- assessment and control of the interface layer i.e. the support fluid/concrete boundary zone
- the contractor's overall experience and capability
- the experience in the site specific ground conditions
- quality of the completed work

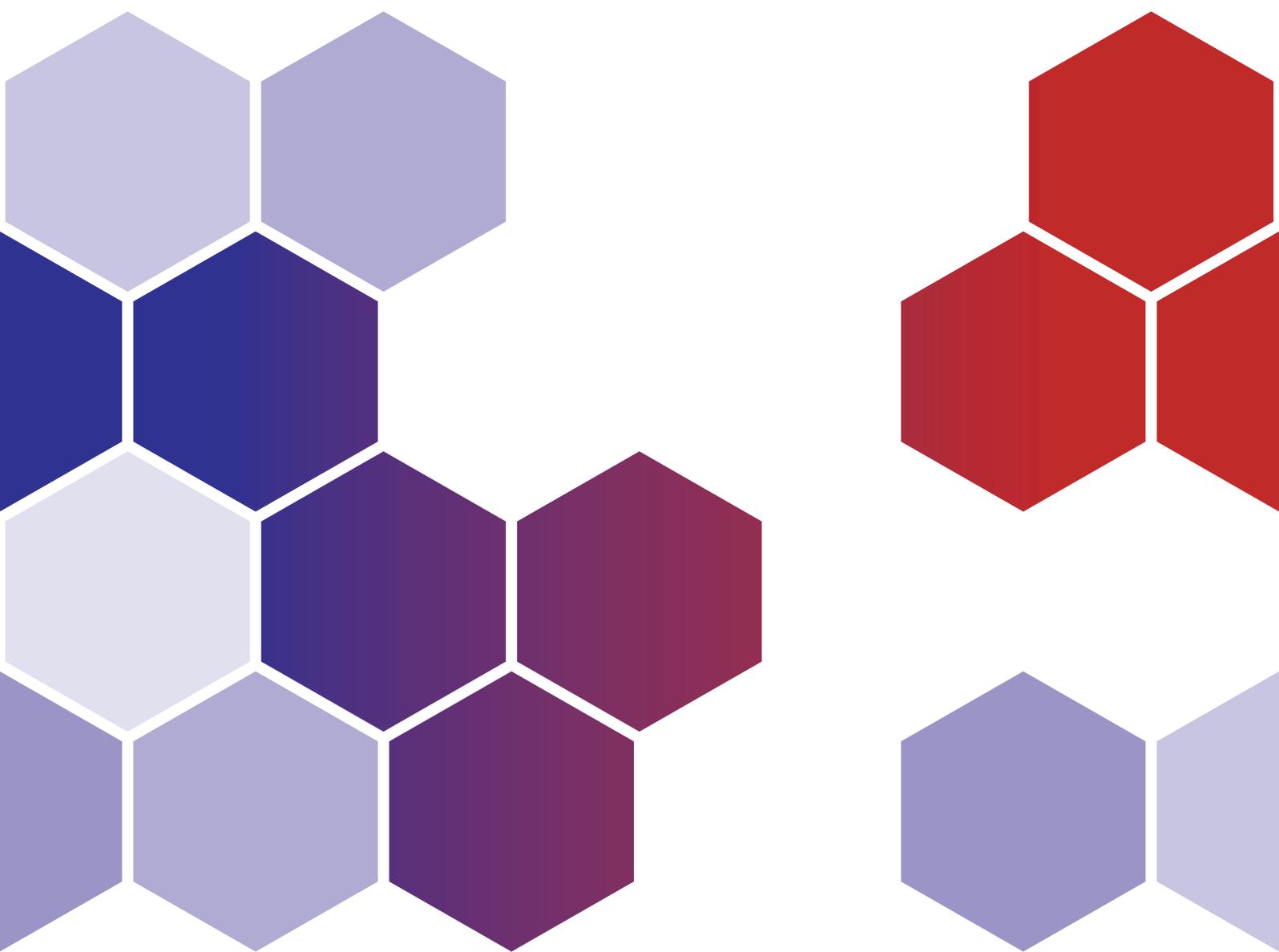
In practice, such trials are best carried out by the appointed contractor after mobilisation to site but prior to commencement of the permanent works. The time and cost of the trial and rectification of any issues arising from the trial should be recognised by the client, and the requirements specified in detail in the tender documents. Such trials can play a significant part in reducing risks for the works and provide opportunity for refinement ahead of the works.

It is important to use support fluid in any trials that is representative of the fluid which will be used during the works. As the trial will use fresh fluid, it may be necessary to load the fresh fluid with excavated material to try and represent working fluid to be used during the works.

When budget and/or time constraints do not allow for such full-scale trials, it is recommended to at least perform on-site support fluid trial testing in close collaboration with the specialist material supplier.

Section 7

Quality Control



7.1 During Construction

During foundation construction, it is essential that the contractor comply with the specified standards for quality assurance and control.

The support fluid quality control issues that apply during construction are listed in *Section 8*. It is very important that good record keeping is undertaken during construction. This will assist in the post construction investigation if there are any imperfections. These records help to establish the reasons for the imperfections and enable subsequent improvements in the construction processes to be made during the work. Hence the trials suggested in *Section 6* are important for improving the quality of the completed works.

7.2 Post Construction

The use of support fluid during excavation and the subsequent tremie concreting processes are intimately linked. *Section 8* of the EFFC/DFI Tremie Concrete Guide sets out a framework for quality control of the completed work. An overview of integrity test methods is provided in *Appendix C* of the EFFC/DFI Tremie Concrete Guide. Three categories of imperfections have been identified below and are discussed in *Appendix D* of the EFFC/DFI Tremie Concrete Guide:

- inclusions
- channelling
- mattressing

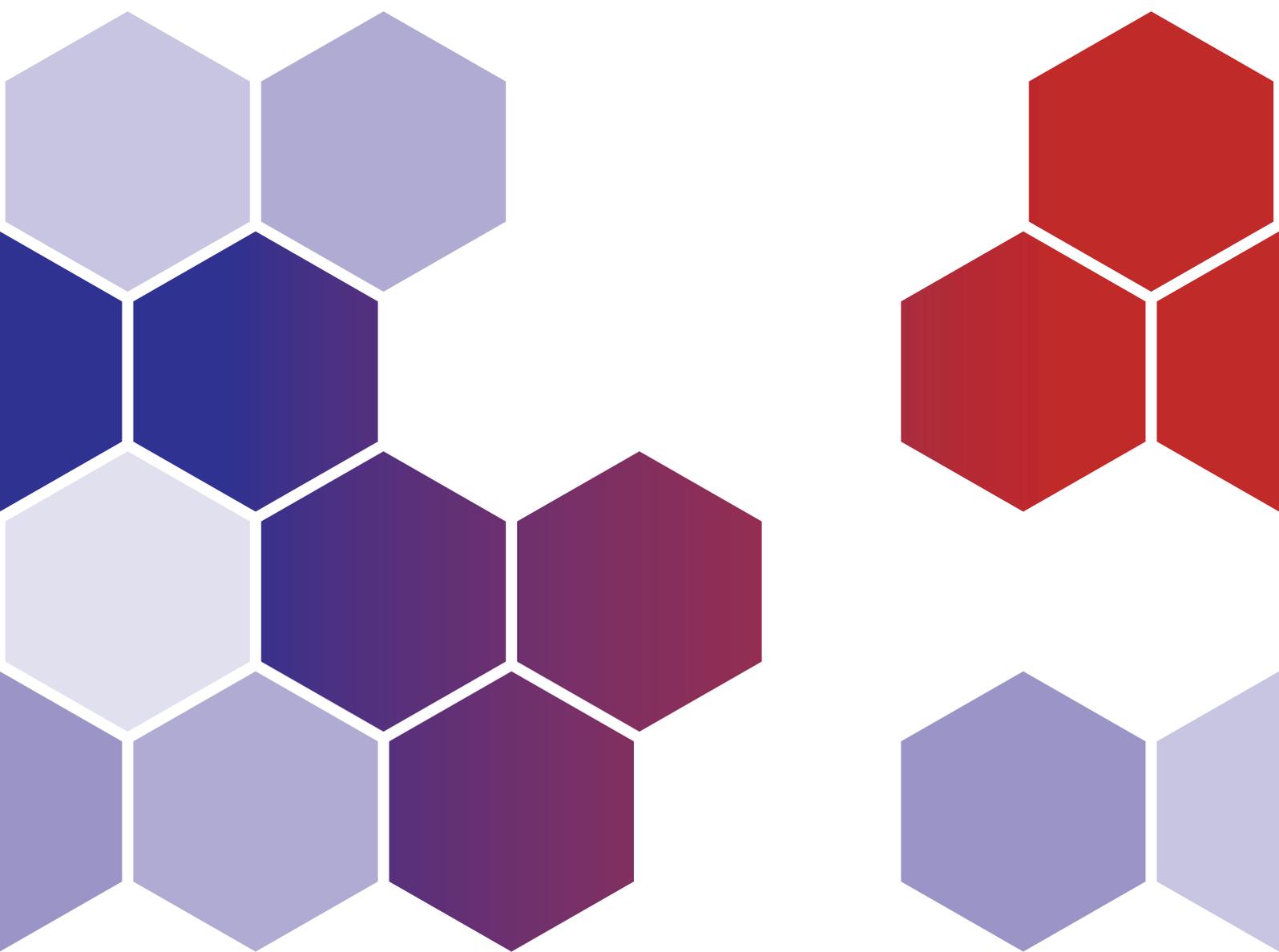
The channelling and mattressing imperfections are normally associated with concrete stability and workability, as well as reinforcement layout (clear spacing, couplers, boxouts, links, tie rods etc). However, the inclusions encountered in completed deep foundation elements can in some instances be associated with poor performance of the support fluid.

Future Developments

The support fluid density profile can be important to assess the sand and clay content. High sand contents can lead to the formation of thick filter cakes as discussed in *Sections 3 and 5.3*. Currently, this is only undertaken occasionally using a sampler. The development of accurate electrical density profilers that can be mounted on a grab or the sampler would be helpful to assess the real time density profile during excavation.

Section 8

Acceptance Values



8.1 Introduction

For any given project, the appropriate support fluid will be selected based first on excavation stabilising performance (fluid rheology), operational efficiency and then availability of resources and previous local experience.

During the execution, properties characterizing a support fluid such as rheology or chemistry are influenced by:

- the ground conditions and environmental considerations
- the type of foundation system being constructed
- the proposed construction method
- the foundation construction cycle

Those properties, determined by the standard tests described must conform to acceptable values in order to ensure the final quality and integrity of the deep foundation element.

The time line of a support fluid during the construction process is shown in *Figure 44* and *Table 10* with a specific set of tests corresponding to each construction step. The specified properties must be checked and maintained at each step using the standard tests described in *Appendix B* to ensure the quality and integrity of the completed works.

FIGURE 43 SUPPORT FLUID TIME LINE DURING THE CONSTRUCTION PROCESS

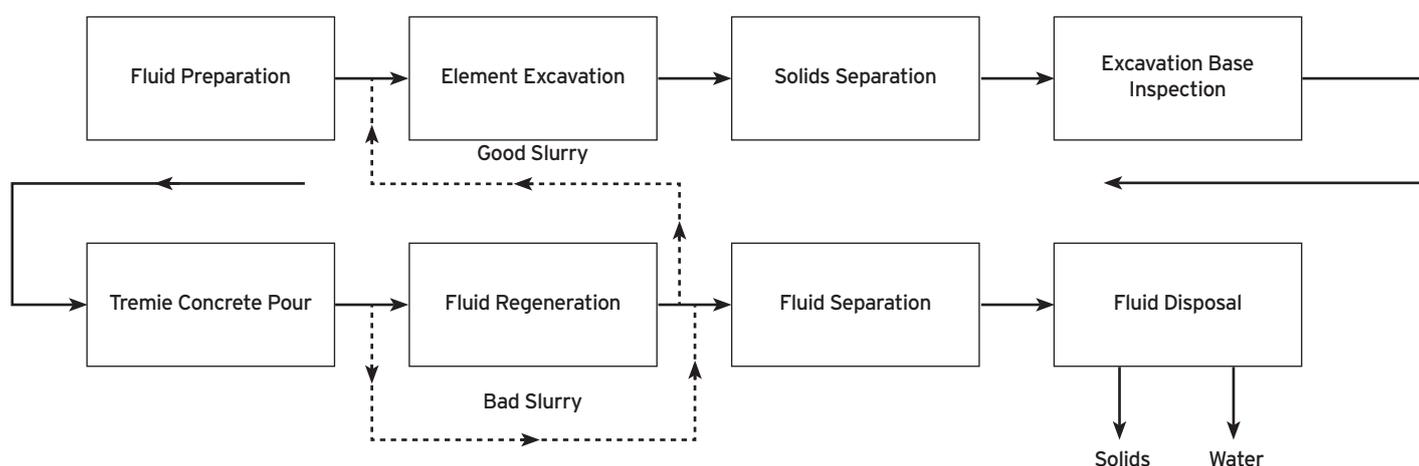


TABLE 10 CONSTRUCTION STAGES

Stage	Activity	Description	Support Fluid Test
1	Fluid preparation	Mixing of fresh fluid	pH, viscosity, density, filter loss
2	Element excavation	Stabilize excavation	Density, filter loss
3	Solids separation	Mechanical, chemical or gravity treatment of fluid	pH, viscosity, density, sand content, silt content (gel strength)
4	Excavation base inspection	Post rebar placement inspection	Sand & silt content, filter cake
5	Tremie concrete pour	Fluid return from concrete pour	Check for cement contamination
6	Fluid regeneration	Mechanical, chemical or gravity treatment of fluid	pH, viscosity, density, sand content, silt content (gel strength)
7	Fluid separation	Waste fluid separation	Sand & silt content, viscosity
8	Fluid disposal	Waste fluid & solid disposal	pH, sand & silt content, oxygen demand

Support fluids are normally re-used from one foundation element to the next, undergoing a recycling/regeneration process after having been subjected to numerous changes during the course of the work. The requirement is to start each new cycle with a support fluid with properties complying with the specified acceptance values. When the specified properties cannot be achieved, the fluid must be discarded.

Stage 1: Fresh Support Fluid

Mixing is covered in *Section 5.1*. Additives are sometimes introduced at this stage to improve the support fluid's initial properties. Mixing water should be tested.

Stage 2: Excavation Support Fluid

Once in contact with the ground the support fluid is subject to multiple effects including (but not limited to) mechanical shearing by the excavation tool, variable filtration according to soil layer permeability, dispersed solids coming into suspension, development of a filter cake, chemical impact from dissolved salts or contaminants, dilution by ground water in saturated soils, and increased filtration caused by a density rise from the suspended solids. All these elements have an impact on the properties of the support fluid, the excavation stability and the mechanical load capacities.

Stage 3: Fluid Cleaning

The quality of the completed foundation element is extremely dependent on the cleanliness of the support fluid prior to the placement of concrete. Mineral fluids are cleaned using well-established mechanical means, possibly with the assistance of chemical additives. The generic terms of 'desanding' and 'desanders' are better referred to as 'solids separation' and 'solids separation plants'. The removal of fines can involve desilting hydrocyclones and centrifuges. Removal of sand is the easy part of the process, removing suspended fines is more laborious. Solids separation from polymer based support fluids is easier since the lack of gel strength allows a rapid segregation of the solids although suspended fines in highly viscous fluids have a much longer settlement speed. Various additives such as coagulants or other cationic additives are used during and after the excavation to accelerate the process.

In deep excavations, where required settlement time would delay the construction process, partial or total replacement (substitution) of the fluid column may often be a quicker option. Where a "twin fluid" system is used (excavation fluid and concreting fluid), it is equally as important to control the properties of the excavation fluid as for the concreting fluid. The excavation fluid can greatly affect the thickness of the filter cake.

Stage 4: Post Rebar Placement Inspection

A cleaned excavation can show unwanted deposits at the bottom of the excavation following the introduction of the reinforcing cage. The causes are multiple: cage slightly off plumb due to poor lifting, excavation not perfectly vertical but still within tolerance forcing the cage to ride on one side of the excavation, inadequate spacers scraping the wall removing filter cake and causing minor sloughing, and excessive soft filter cake thickness (due to high filtrate loss) being scraped systematically on the way down. The amount of accumulation of these deposits at the bottom of the excavation needs to be determined by measurement and deep sampling to decide if any additional cleaning measures are required. Minor amounts of material can be removed by pumping from the tremie pipe or using an airlift.

In this analysis, accuracy of depth measurement is crucial, comparing the excavation depth at the end of cleaning to that at the end of the rebar cage placement. In addition, if any delay is involved from the time a cage is placed and the start of the tremie concrete pour, a second sounding is necessary to assess the possible sedimentation at the bottom. This is particularly important when using polymer support fluids.

Stage 5: Support Fluid Return from Concrete Pour

Support fluid being displaced by the tremie concrete is returned to the storage area in a condition that can be quite different from that following cleaning in Stage 3. For bentonite based fluids, cement contamination will have a detrimental effect on viscosity and filtration properties and intermixing between support fluid and concrete will normally require the bentonite displaced near the end of the pour to be sent to waste. In the case of polymer fluid, the silt laden lower portion of the column is directed to a dedicated settling tank where settled silt can be easily removed. Heavy cement contamination leads to high pH values that can degrade the polymer fluid.

Stage 6: Support Fluid Regeneration

The objective of regenerating the support fluid is to bring it back to as close to a fresh support fluid condition as possible to repeat the construction cycle a number of times and avoid the unnecessary disposal of fluid. Several techniques specific to either bentonite or polymer fluids are implemented, requiring a high level of qualification on the part of the "mud man". A constant balance between the cost of regenerating the fluid and the cost of disposal must be made to produce a positive economic outcome.

Stage 7: Waste Fluid Disposal Process

Either when regeneration becomes prohibitive or at the end of the foundation construction project, support fluids need to be processed to allow the economical disposal of the ingredients while respecting all applicable environmental regulations.

Mineral fluids need to combine chemical and mechanical conditioning allowing the separation of the water phase from the solids phase resulting in a small volume of residual fluid. The extreme case is the solidification with a cementitious binder for removal as spoil.

Polymer support fluids can be prepared for disposal using strong oxydisers which break the links forming the long chains and reduce the viscosity close to that of water thus allowing the fast settlement of all suspended fines. With proper coordination, local water treatment plants accept residual polymer fluid provided pH levels are corrected and no objectionable dissolved additives are present. This process may require large storage capacities to allow time for the polymer to be broken down.

Stage 8: Support Fluid Residuals for Offsite Disposal

Residual water either from bentonite fluid dewatering or polymer fluid breakdown are typically authorised after proper approvals from local water treatment plant authorities.

Non-contaminated solids are treated as soil and disposed in landfills or re-used. When solids have been solidified with a cementitious binder, an off-site disposal permit may be required to satisfy Local Authority requirements.

8.2 Frequency of Testing

There is little guidance within current standards as to the required frequency of testing. Conformity testing is an integral part of the production control to ensure the quality of the permanent works.

The evaluation of conformity is the systematic examination of the support fluid throughout each production stage, ensuring all the specified requirements are achieved.

Tables 11 and 12 give test methods for each stage for bentonite and polymer fluids with recommended frequencies. The frequencies given in the Tables should be considered as minimum values. More frequent tests are required at the start of the work to establish trends. Significant variations in results will normally also require more frequent testing.

TABLE 11 APPLICABLE TESTS AND MINIMUM FREQUENCY FOR MINERAL, NATURAL POLYMER AND MODIFIED NATURAL POLYMER SUPPORT FLUIDS

Test	Test Method	S1 Fresh Fluid	S2 Excavation Fluid	S3 Before Concreting	S5 & S6 Fluid for Reuse
Frequency		daily	once per element	before pour	daily
Viscosity	Marsh Funnel	M	R	M	M
Density	Mud balance	M	R	M	M
Sand content	Sand content kit	N/A	R	M	R
pH	pH-paper	M	R	M	R
Filter loss	API filter press	M	R	M	M
Filter cake thickness	API filter press	M	R	M	M
Silt content	Calculation	N/A	N/A	O	O
Gel strength	Fann Viscometer	O	N/A	O	O

M : mandatory, R : recommended, O : optional, N/A : not applicable

Table 11 is also applicable for hydromill operations using modified natural polymer. In this case, filter loss and filter cake thickness does not apply for fresh fluid as there are no particles in suspension at that time.

TABLE 12 APPLICABLE TESTS AND MINIMUM FREQUENCY FOR SYNTHETIC POLYMER SUPPORT FLUIDS (EXCEPT FOR HYDROMILL)

Test	Test Method	S1 Fresh Fluid	S2 Excavation Fluid	S3 Before Concreting	S5 & S6 Fluid for Reuse
Frequency		daily	once per element	before pour	daily
Viscosity	Marsh Funnel	M	R	M	M
Density	Mud balance	M	R	M	R
Sand content	Sand content kit	N/A	R	M	R
pH	pH-paper	M	R	R	M
Filter loss	API filter press	N/A	N/A	N/A	N/A
Filter cake thickness	API filter press	N/A	N/A	N/A	N/A
Silt content	Calculation	N/A	N/A	O	O

M : mandatory, R : recommended, O : optional, N/A : not applicable

Mixing water should be tested and controlled prior to commencing the project to ensure its suitability with the selected materials to produce a fresh mix with characteristics complying with the specification.

Typically, it is recommended to test mixing water for pH, electrical conductivity, calcium, magnesium and chlorine.

8.3 Existing Standards

On both sides of the Atlantic, government agencies involved with infrastructure construction as well as private professional associations have contributed to the creation of standards. A need for unified standards is obvious but difficult to accomplish given the wide variety of situations involving the deep foundations industry including the various modes of contracting and procurement.

By standards we mean a number of measurable properties that characterize the nature and properties of a support fluid. These properties are described in *Section 8.2* of this Guide. Not all measurable properties are incorporated in the current standards since these represent to a large extent a state of practice more than an exhaustive list of measurable characteristics, such as yield stress, gel strength and silt content which are at present excluded from most standards. A summary of acceptance values used in some existing standards is given in *Table 13* for bentonite, and *Table 14* for polymer.

TABLE 13 CURRENT ACCEPTANCE VALUES FOR MINERAL, BLENDED, NATURAL POLYMER AND MODIFIED NATURAL POLYMER SUPPORT FLUIDS

Properties	Viscosity	Shear Strength	Density	Fluid Loss	Cake	pH	Sand Content
	s/qt	N/m ²	g/ml	ml at 30 mins	mm at 30 mins		%
Freshly Mixed							
EN1536/1538	32-50		< 1.1	< 30	< 3	7-11	
ICE SPERW	30-50	4-40	< 1.05	< 30	< 3	7.5-11	
ACI 336.1	26-50						
FPS	32-50		1.1	< 30		7-11	
FHWA/AASHTO	28-50		1.03-1.15			8-11	
DFI Manual	>32		> 1.03	< 25		7-11.5	
Caltrans	28-50		1.03-1.11			8-10.5	
Ready for Reuse							
EN1536/1538	32-60		< 1.25	< 50	< 6	7-12	
ICE SPERW	30-60	4-40	< 1.08	< 50	< 6	7.5-12	
ACI 336.1							
FPS	32-60		1.25	< 50		7-12	
FHWA/AASHTO	28-50		1.03-1.15			8-11	
DFI Manual							
Caltrans	28-50		1.03-1.11			8-10.5	
During Excavation							
EN1536/1538							
ICE SPERW			< 1.35		< 15	7.5-12	
ACI 336.1						7-12	
FPS							
FHWA/AASHTO	28-50		1.03-1.15			8-11	
DFI Manual	< 50		< 1.12				
Caltrans	28-50		1.03-1.11			8-10.5	
Prior to Concreting							
EN1536/1538	32-50		< 1.15*				
ICE SPERW	30-50	4-40	< 1.10		< 3	7.5-12	< 2**
ACI 336.1			≤ 1.36/≤ 1.12				≤ 20/≤ 4
FPS	32-50		< 1.15				≤ 4
FHWA/AASHTO	28-50		1.03-1.15			8-11	≤ 4
DFI Manual	< 50		< 1.12				≤ 5***
Caltrans	28-50		1.03-1.11			8-10.5	< 4

* A density of 1.20 is acceptable in salt water or soft soil; and 6% of sand content in unreinforced concrete

** 4% sand content is permitted where base cleanliness and end bearing performance is not critical.

*** Sand content can be reduced to about 1 to 2% in case of deep foundations.

ACI 336.1 : For the same property, the left hand number is without end bearing consideration and the right hand number is with end bearing consideration

TABLE 14 CURRENT ACCEPTANCE VALUES FOR SYNTHETIC POLYMER SUPPORT FLUIDS (EXCLUDES HYDROMILL)

Properties	Viscosity	Shear Strength	Density	Fluid Loss	Cake	pH	Sand Content
	s/qt	N/m ²	g/ml	ml at 30 mins	mm at 30 mins		%
Freshly Mixed							
EN1536/1538							
ICE SPERW**	> 90		1.01		*	9-11	0
ACI 336.1	40-90						
FPS							
FHWA/AASHTO	32-135		≤ 1.03			8-11.5	
DFI Manual	40-90		≤ 1.03				
Caltrans							
Ready for Reuse							
EN1536/1538							
ICE SPERW**	60-120		< 1.02		*	9-11.5	< 2
ACI 336.1							
FPS							
FHWA/AASHTO	32-135		≤ 1.03			8-11.5	
DFI Manual	40-90						
Caltrans							
During Excavation							
EN1536/1538							
ICE SPERW**	60-120		< 1.05		*	9-11.5	< 5
ACI 336.1						7-12	
FPS							
FHWA/AASHTO	32-135		≤ 1.03			8-11.5	
DFI Manual	40-90						
Caltrans							
Prior to Concreting							
EN1536/1538							
ICE SPERW**	90-120		< 1.02		*	9-11.5	< 1
ACI 336.1			≤ 1.03/≤ 1.03				≤ 1/≤ 1
FPS							
FHWA/AASHTO	32-135		≤ 1.03			8-11.5	≤ 1
DFI Manual	40-90		≤ 1.03				≤ 1
Caltrans							< 2

* see Table C20.2 of ICE SPERW

** polyacrylamide polymers for use in bored piles

ACI 336.1 For the same property, the left number value is without end bearing consideration and the right hand value is with end bearing consideration.

The Field Research Study will carry out a number of non-standard tests with the intention of determining their practicality and usefulness, including some of the following:

- silt content: although silt content has no standard test at this time, silt can be the cause of various types of construction defects. Presently, silt content is measured indirectly through density measurement. Direct measurement using a crank centrifuge may be possible although further work is required to produce calibrations
- bentonite content: this is not normally an issue as long as the filter loss remains low, although it can be useful to confirm batch mix calibration
- polymer content (important to analyse changes in fluid behaviour, especially when allowing higher densities)
- yield stress (mainly for mineral fluids)
- resistivity (detects presence of electrolytes that can affect most support fluids)
- cement contamination of bentonite fluid during concreting (increased pH is the easiest indicator)
- residual chlorine (polymer only): residual chlorine (oxydizer) in many urban distribution systems may destroy some of the polymer. Polymer suppliers should provide chlorine content limits for use with their products. This can also be relevant for bentonite extender polymers
- filter loss at 10 psi: The API standard filter test at 100 psi represents nearly 70 m [230 ft] of water hydrostatic head differential which is unrealistic for foundation work and it should be seen only as a bentonite quality control test. A 10 psi pressure represents 7 m [23 ft] differential head which covers most foundation cases. At that pressure, pure polymer fluids may be tested for filtration, although clean PHPAs will still give high results

No guidance is currently given on the order of importance of the test values which should be as shown below, although a thorough review of all results is still critical to the management of all fluids:

- density (affects excavation stability)
- filter loss (reduce loss to the soil/excavation stability)
- filter cake thickness (loss of cover, shaft resistance and interface layer)
- sand content (filter cake thickness and quality of the base)
- silt content (can be as important as sand content, especially with polymer fluids, but currently no standard test)
- pH (a useful indicator but not a control)

The Task Group has obtained sponsorship to carry out a Field Research Study to review current standards and practices from around the World. In addition, sites will be visited to assess what is current practice in both Europe and North America. During the site visits, additional non-standard testing will also be carried out (e.g. composition and properties of the interface layer). It may also require laboratory tests to be carried out to determine the effect of the fluid parameters on concrete flow.

It is intended that this work will take approximately two years starting in 2019. A 2nd Edition of this Guide is then planned and this will contain recommendations and further guidance for the fluid types commonly used in the construction of deep foundations.



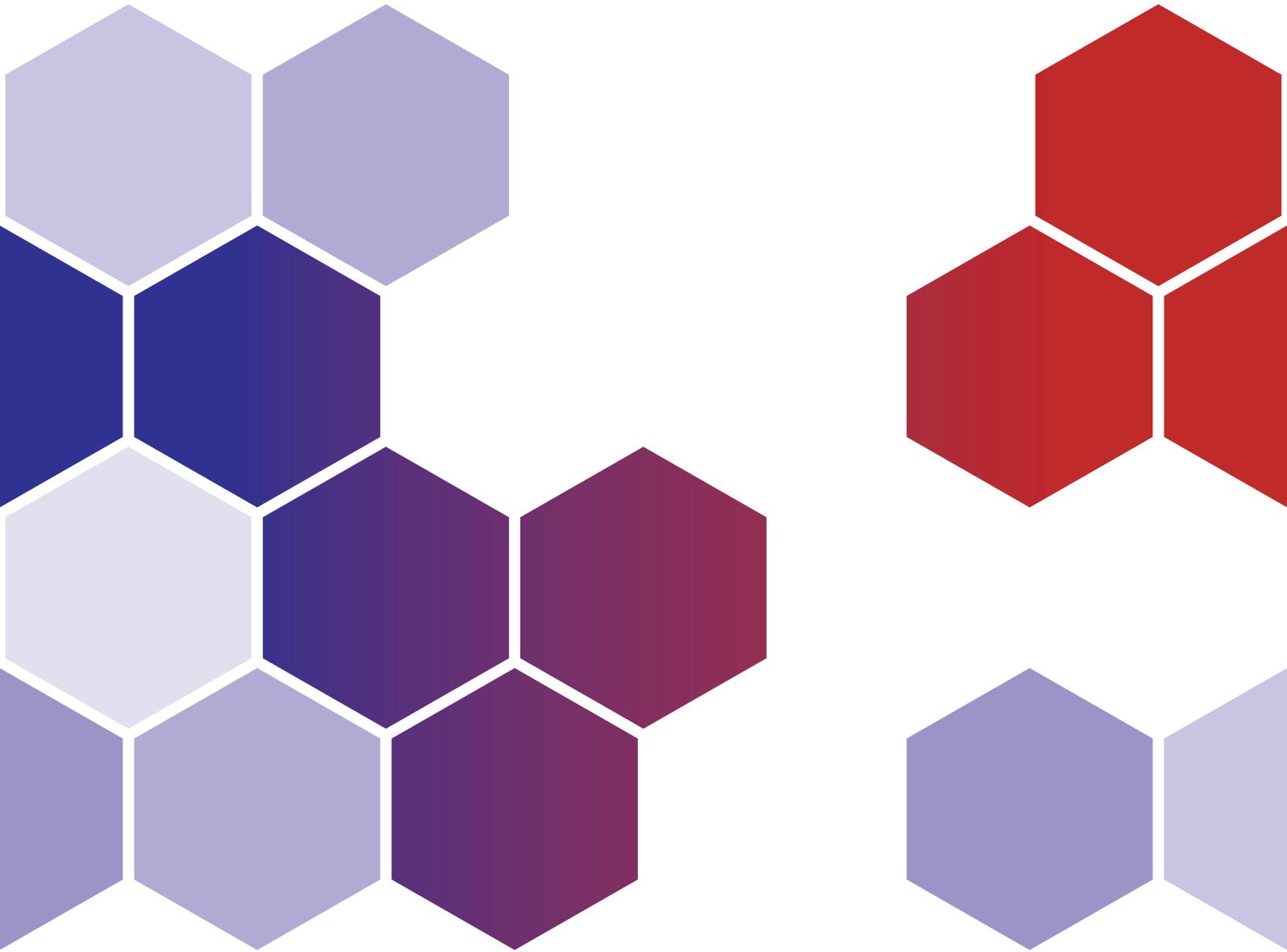
8.4 The Route Forward

Current standard tests do not generally cover all the fluid types available for use in deep foundations.

The value of each individual standard test has little interest if not taken in relation to the other values, and the evolution of values through the construction stages is more important than one isolated value. Determining why the test values are evolving is as important as individual results. This may require greater operative training and/or input from experienced engineers.

Whilst the mud balance is given as the standard test to measure density, the accuracy of the test is not high enough to be of value with polymers (and fresh bentonite fluids). Agitation of mineral fluids is rarely specified before viscosity measurements using a Marsh Funnel.

Appendix A



A.1 Failure Mechanisms

There are three main failure mechanisms for open excavations:-

1st Mechanism: Hydraulic Failure due to Flow of Groundwater Towards the Excavation

If the groundwater pressure exceeds the supporting fluid pressure inside the excavation the resulting hydraulic force will be destabilizing and hydraulic failure is very likely. Critical situations could be:-

- encountering a confined aquifer with high groundwater level
- saline groundwater (with high specific weight) in combination with low weight slurry (e.g. polymer fluid mixed with fresh water and without a significant fines content)
- sand or gravel lenses in fine soils or soils that are enclosed by previously completed panels where the groundwater pressure will rapidly increase
- a loss of slurry pressure due to a piston effect if the tool is withdrawn too quickly or is not properly designed (bypass channel too small)
- when using an air lift, the introduction of air bubbles at the base of the excavation may effectively reduce the unit weight of the support fluid

It is critical that the support fluid pressure sufficiently exceeds the groundwater pressure during all construction phases.

2nd Mechanism: Single Grains or Small Groups of Grains Falling off the Excavation Walls

If grains at the excavation walls cannot be kept in place this may result in a progressive failure of the excavation.

Grains are pushed against the wall by the horizontal flow force $i \cdot \gamma_F \cdot V$. This flow force is a mass force which results from the hydraulic gradient i within the volume V of the considered grains.

In case of a bentonite suspension with a yield strength this mass force may be applied by static shear stresses after the penetration has stagnated. The horizontal flow force mobilizes an upward friction force which must be greater than the gravitational force of the grains (with buoyant specific weight under supporting fluid) to prevent sliding. It is essential that a suitable seal is maintained at or within the excavated surface.

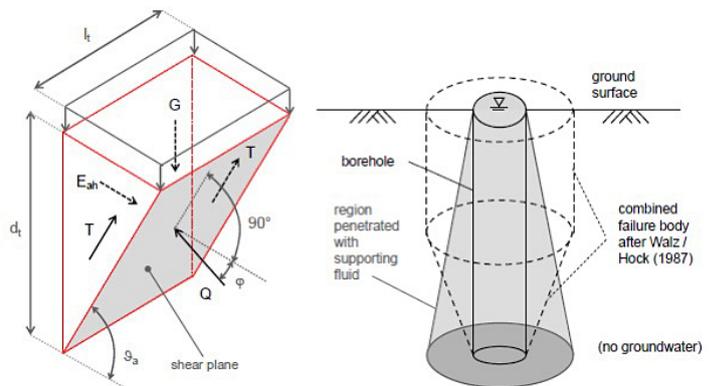
3rd Mechanism: Failure Body Sliding on a Shear Plane

If the hydraulic supporting force falls below a critical limit a failure body may slide on a shear plane ϑ_a .

This could be a failure body according to DIN 4126 (see Figure A.1 with critical angle of shear plane ϑ_a , gravitational force G , variable load p , shear force Q and shear forces T in the lateral faces).

Other failure body geometries should be considered if conditions are complex (e.g. inclined ground surface or layered ground). A reduction of the trench length (l_t in Figure A.1) increases the influence of the lateral shear forces (T) and the level of safety. For a circular excavation, a failure body as shown on the right side of Figure A.1 may be considered. *Note: a 3D failure body model naturally covers "arching effects".*

FIGURE A.1 EXAMPLE OF CRITICAL FAILURE BODY FOR A TRENCH (LEFT, AFTER DIN 4126) AND A CIRCULAR EXCAVATION (RIGHT)



A.2 Considerations on Hydraulic Support Forces

The supporting fluid generally opposes a total supporting force to the surrounding soil which is independent of its penetration and equals the hydrostatic force given by the fluid level in the excavation. However, this total force is only available for the support of the critical failure body if a seal of low permeability (membrane) builds up on or near the surface of the soil. In this case the support fluid exerts its maximum stabilizing effect.

If there is no such membrane the supporting fluid will penetrate to some extent into the formation. In this case only a part of the supporting force is transferred within the relevant failure body and the effective supporting force must be taken into account.

The maximum penetration of a bentonite fluid is limited by clogging by solids in the excavation fluid helped by the gelation of the fluid (gel strength). Once the hydraulic gradient has decreased to a "stagnation gradient" the fluid is able to hold on the pore channels with its shear strength.

The maximum penetration of a polymer slurry is theoretically not limited because these fluids typically do not have a relevant yield strength. However, penetration will still slow down over time due to a decreasing hydraulic gradient. This effect is even stronger due to the pseudoplastic rheology of most polymer slurries (viscosity increases with decreasing shear rate)

and penetration rates are sometimes so small that stagnation may be assumed. However, for polymer slurries a possible decrease of support forces over time should be taken into account. Stability assessment should be based on the maximum time needed for completion of the pile or panel.

Penetration and resulting support forces are not only governed by rheological fluid properties. Particles suspended in the support fluid due to excavation operations or added intentionally to assist pore blocking will form a filter cake inside the formation. This results in reduced penetration rates and an increased effective supporting force.

Stability Check Methods

Trial excavations, experience in equivalent or similar conditions or analytical stability checks can be applied to assess excavation stability.

Trial Excavations

Trial excavations give the best provision for real site conditions and are strongly recommended if no experience is available for the relevant conditions. However, to assess a level of safety from the test result special measures must be taken (e.g. lower support fluid level in trial excavation). Additionally, analytical estimations can help to decide what slurry parameters should be used for the trial as parameter variations would require several trials and cost time and money. Also, the failure of a trial excavation might not be acceptable in urban areas and in this instance reliance should be made on previous experience in similar conditions and/or additional calculations.

Experience in Equivalent or Unfavorable Conditions

Experience in equivalent or similar conditions may be a quick and easy method to evaluate the stability of an excavation. Additionally, experiences should always be taken into account for first assessment and plausibility checks even if other methods of stability checks are used. It is important to mention that the comparison of project conditions is often difficult. Stability is influenced by many factors such as geometry of the excavation, support fluid parameters (e.g. components, dosage, quality of mixing water, mixing technique), soil properties (e.g. layers, porosity, permeability, shear strength), ground water level, external loads, depth of guide wall or casing, execution time etc.

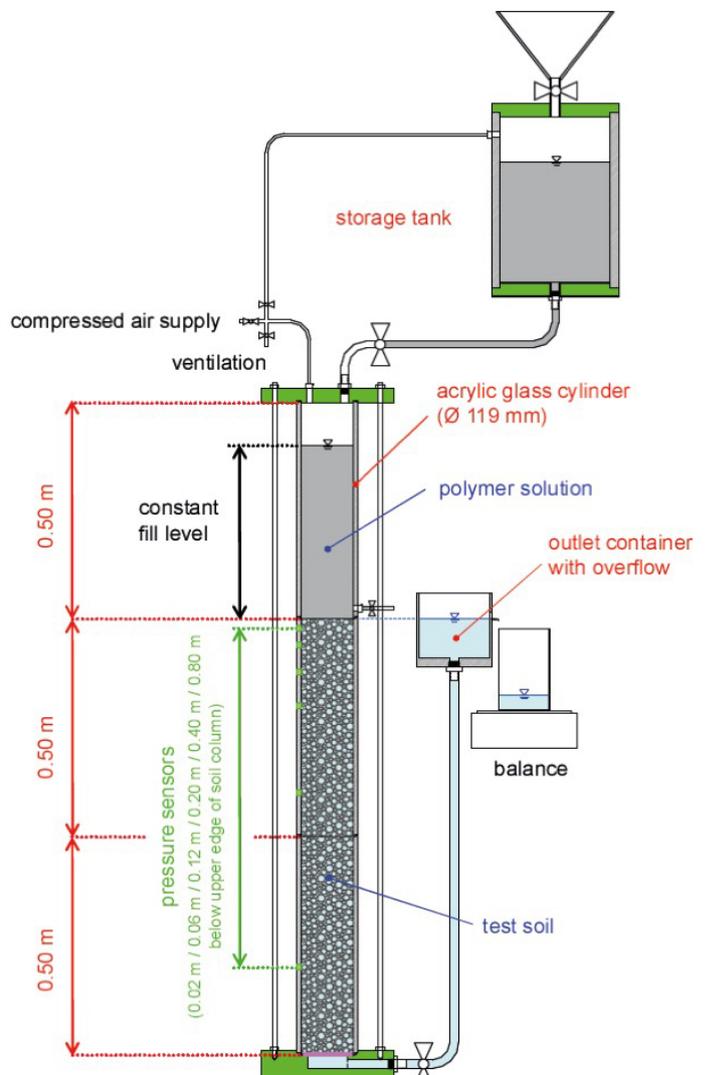
Analytical Stability Checks

Analytical stability checks allow all relevant parameters of influence to be taken into account and to detect failure mechanisms, to optimize design and to compare the performance of different products in an objective way. The calculation of penetration lengths, hydraulic gradients

and support forces requires the determination of rheological parameters (e.g. power law parameters to describe pseudoplastic rheology). This can be achieved with the flow test shown in Fig. A.2 that also allows the hydraulic head loss along the penetration length to be measured. Similar tests may be performed if the calculation for a support fluid is done using a stagnation gradient (fluid with gel strength).

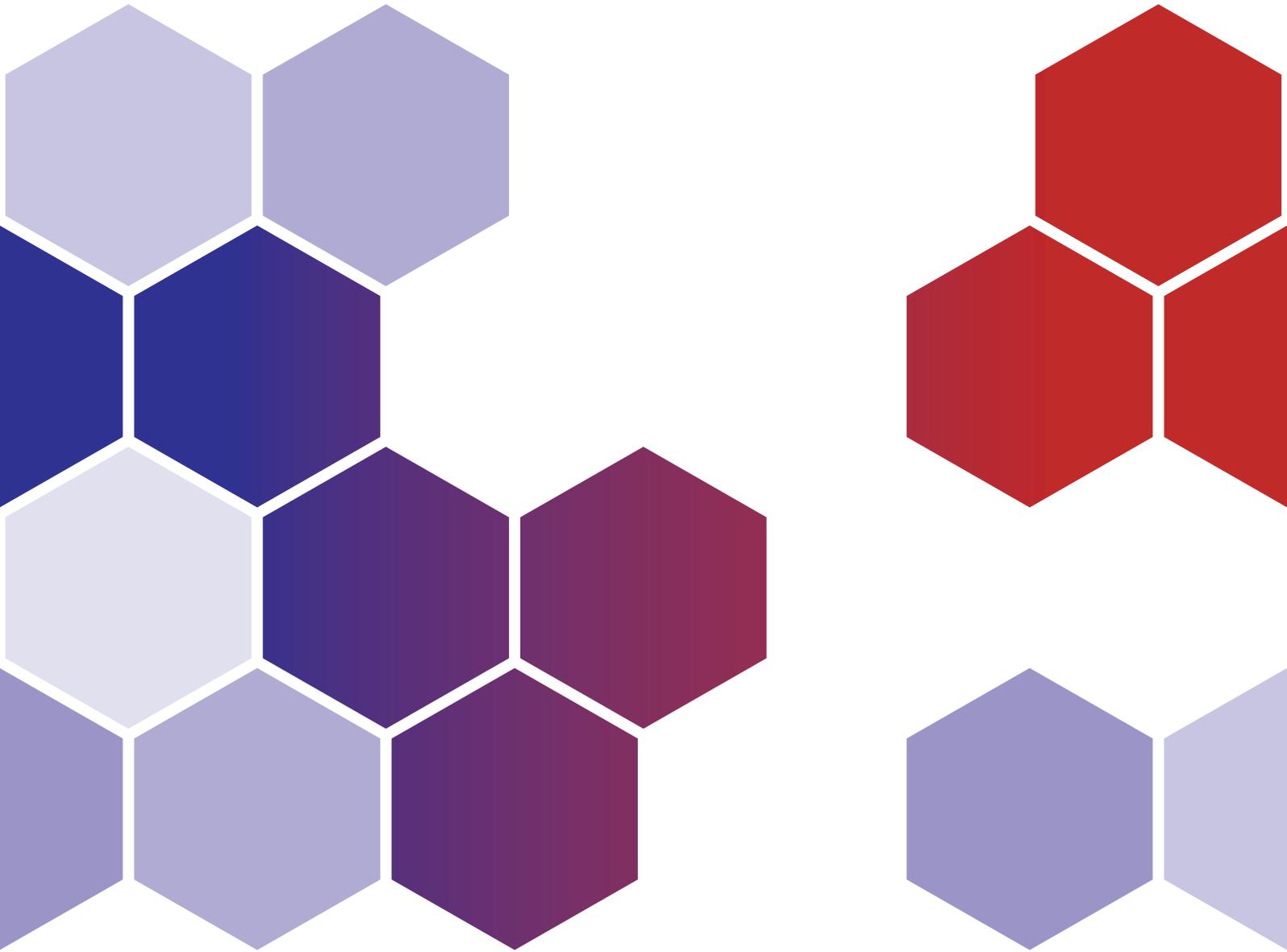
The time-dependent penetration of a support fluid based on rheological parameters may be calculated according to Lesemann [2016, DOI: <http://doi.org/10.3846/13bsgc.2016.035>].

FIGURE A.2 FLOW TEST (LESEMANN, 2016)



For calculating trench stability according to DIN 4126, "Trench" software is available from GGU Software.

Appendix B



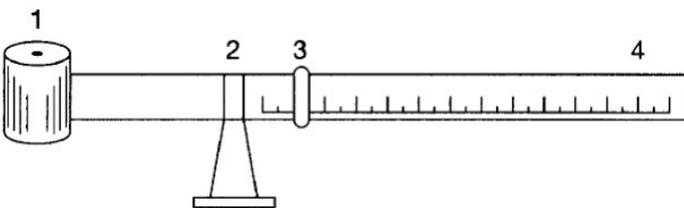
B.1 Density

For support fluids, the most usual instrument for density measurements is the mud balance. The instrument consists of a cup rigidly fixed to a scale arm fitted with a sliding counterweight or rider (Figure B.1). In use the whole unit is mounted on a fulcrum and the rider adjusted until the instrument is balanced. The fulcrum must be placed on a horizontal surface. Specific gravity can be read from an engraved scale. It should be noted that the instrument may have three scales in addition to the specific gravity scale but none of these scales is required for civil engineering work.

As the balance was developed for the oil industry, the range of the instrument is wider than necessary for civil engineering works.

The balance may be checked by measuring the water density which has to be equal to 1.00.

FIGURE B.1 SCHEMATIC DIAGRAM OF THE MUD BALANCE: (1) MUD CUP, (2) FULCRUM, (3) RIDER, (4) SCALE

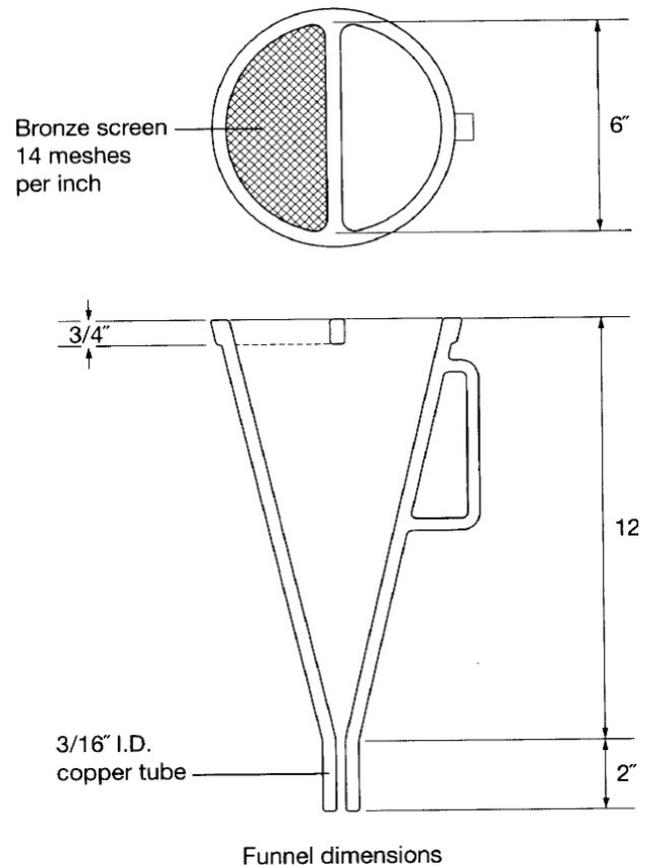


The density of many polymer support fluids is close to that of water and the mud balance is not sensitive enough. It is therefore recommended that density is measured using a weigh balance with a suitable container calibrated for volume (Jefferis and Lam 2017).

B.2 Marsh viscosity

The Marsh funnel is the simplest instrument for routine assessment of support fluid flow behavior. The test procedure is simply to pour a freshly stirred sample of support fluid through the screen to fill the funnel to the underside of the screen **at the scribed line** (a volume of 1.5 liter). Then measure the time for the discharge of 946 ml (1 US quart) of support fluid from the funnel (Figure B.2). The result is quoted as Marsh funnel seconds. The Marsh funnel time in seconds cannot be directly converted to a viscosity. All Marsh Funnel times quoted in this Guide are for 946 ml.

FIGURE B.2 THE MARSH FUNNEL



The funnel may be checked by measuring the flow time for water. For clean water at 21°C (70°F) the times should be as follows:-

- For 946 ml - 25.5 to 26.5 s
- For 1000 ml - 27.5 to 28.5 s

No adjustment of the funnel is possible, and if readings outside the above ranges are obtained it must be assumed that the funnel (or the stopwatch) is damaged. Nevertheless a higher water test value could highlight the funnel cleaning need.

B.3 Filter Loss/Filter Cake

Filter loss will be significant for support fluids as they are all segregation processes that lead to loss of product volume. At its simplest, filtration is a pressure-driven process whereby a particulate system, when pressurized against a permeable formation, deposits a filter cake which accretes with time under pressure and which controls the rate of loss of water. The filtration is controlled by the loss of liquid (water)

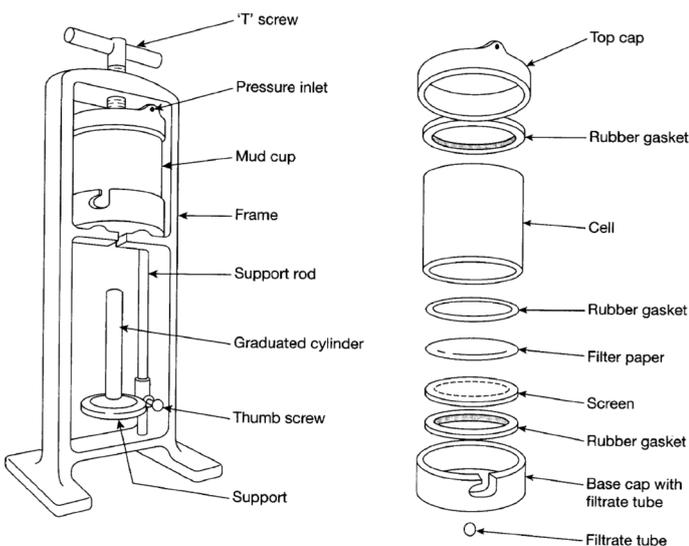
Appendix B: Support Fluid Tests

through a solid system - a filter cake - while bleeding is controlled by the behavior of a fluid system.

The standard apparatus used for filter loss measurement is the American Petroleum Institute filter press apparatus developed for testing drilling fluids (API 13B 2003). The instrument consists of a 3 inch diameter cell with a detachable base in which a filter paper supported on a wire mesh can be fitted as shown in Figure B.3. The filter paper is a Watman hardened filter paper with 2.7 μm openings. In the standard test the volume of filtrate collected from a support fluid sample subjected to a pressure of 100 psi (689 kN.m⁻²) for 30 minutes is measured.

The thickness of the cake is measured at the end of the test, and the permeability of the cake can be estimated by a function of the applied pressure.

FIGURE B.3 STANDARD FILTER PRESS AND MUD CELL ASSEMBLY



B.4 pH

pH is a measure of the acid or alkaline nature of a material. pH 7 is neutral; below 7 is acid; above 7 is alkaline. pH may be measured with a glass electrode and a matched millivolt meter or with pH papers.

The relative acidity or alkalinity of a liquid is conveniently expressed as pH. Defined as the negative logarithm (to the base 10) of the hydrogen-ion concentration, pH units decrease with increasing acidity by a factor of 10.

$$\text{pH} = -\log[\text{H}^+]$$

where $[\text{H}^+]$ is the hydrogen ion concentration in moles per liter. At room temperature, the ion product constant of water, K_w , has a value of 1×10^{-14} mol/L.

$$K_w = [\text{H}^+][\text{OH}^-] = 1.0 \times 10^{-14}$$

For pure water, $[\text{H}^+] = [\text{OH}^-] = 1.0 \times 10^{-7}$ and hence, $\text{pH} = 7$.

pH may be measured with a glass electrode and a matched millivolt meter or with pH papers.

With an electrode it should be possible to measure the pH of pure solutions to a repeatability of better than 0.05 pH unit, though it will be necessary to calibrate the electrode with a buffer solution prior to test. Ideally two buffer solutions should be used with a pH range that brackets the expected pH of the support fluid. But the use of an electrical pH meter may be regarded as excessive and reserved for laboratory situations.

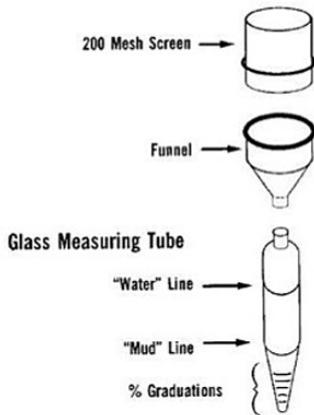
With pH papers, by selecting narrow range papers it is possible to measure pH to 0.1 unit. When testing suspensions, to avoid masking the colour with deposited solids apply the suspension to one side of the paper and read the colour from the other. It is also possible to test the filtrate from the filter loss test to avoid colouration problems. The pH paper must be stored in a sealed container to protect it from ambient humidity.

B.5 Sand Content

During the excavation the support fluid density will increase due to suspension of soil. This density provides a measure of the total amount of soil in the support fluid but no information as to whether this is sand, silt or clay.

The sand content test is designed to measure the bulk volume of sand (strictly material coarser than 200 mesh US, 0.075 mm, 75 μm) in a given volume of fluid. The apparatus consists of a tapered graduated tube, a small 200 mesh US sieve and a funnel (Figure B.4). To carry out the test, a fixed volume of support fluid is washed on the screen and the volume of retained soil is measured as a fraction of the original support fluid volume. The result of the test is quoted as the sand content.

FIGURE B.4 THE SAND CONTENT TEST EQUIPMENT



B.7 Effective Yield Point

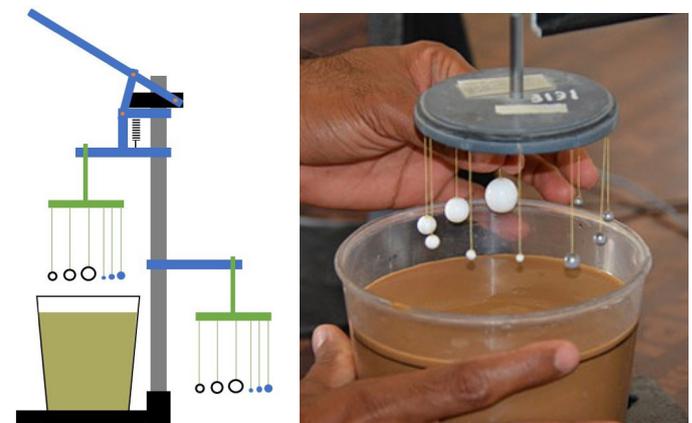
This test setup is standardized in DIN 4127. The so-called Ball Harp is used to determine the effective yield point of support fluids according to the former version of DIN 4126 and is still in use due to its uncomplicated and fast method of measuring the yield point of a suspension.

The Ball Harp equipment consists of a set of 10 glass and steel balls with different diameters. They are attached with polyamide threads to a common disk, the disk can be mounted on a drill stand. The fluid sample is placed beneath the balls and stirred up with a whisk to reduce thixotropic effects, then the ball set is dipped slowly by use of the drill stand's lever, in order to avoid dynamic effects.

Depending on the previously measured density of the support fluid, each ball is assigned to a specific critical effective yield point, at which it would just be buoyant. Balls, whose critical yield point is below the fluid's yield point, float on it (thread bent). The critical effective yield points of all balls are displayed in a table for all consecutive ball numbers and all fluid densities between 1.02 and 1.32 g/cm³ [64 and 82 lb/ft³] and yield points between 7 and 70 Pa [15 and 145 lb/100ft²]. The effective yield point of the support fluid can thus be estimated between the critical yield point of the ball with the largest number which is still floating and the critical yield point of the ball with the smallest number which is immersed.

Two sets of balls, a cup filled with fresh water for cleaning purposes and a cold air fan allow for continuous measurement of test samples.

FIGURE B.6 BALL HARP TEST ACCORDING TO DIN 4127



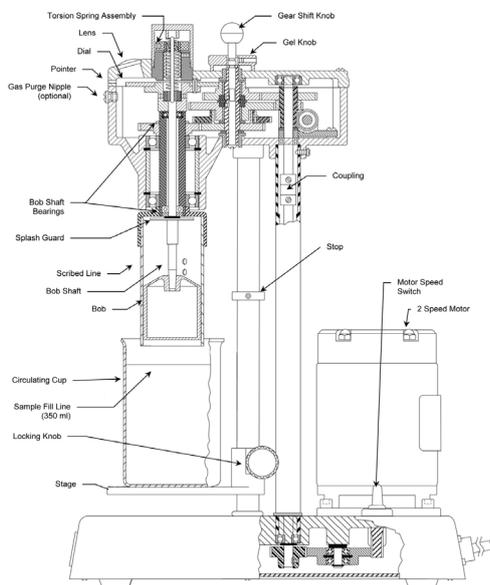
B.6 Gel Strength

Gel strengths are determined using a two-speed direct-indicating viscometer by slowly turning by hand the driving wheel on the top or side of the instrument and observing the maximum deflection before the gel breaks. The same procedure is followed in the multispeed viscometer, except that the cylinder is rotated at 3 rpm with the motor.

The maximum deflection is the gel strength. Gel strengths are measured after allowing the mud to stand quiescent for any time interval of interest, but they are routinely measured after 10 s (initial gel strength) and 10 min. The dial reading gives the gel strength in pounds per hundred square feet.

The thixotropy is characterized by the difference between the reading at 10 s and the reading at 10 min.

FIGURE B.5 FANN VISCOMETER



B.8 Calcium

Hardness in water is caused by the presence of calcium ions, magnesium ions, or both. As their concentrations increase, water becomes harder. The combined concentration of calcium and magnesium is frequently referred to as total hardness.

Temporary Hardness

Temporary hardness is that due to calcium and magnesium ions in the water associated with carbonate and bicarbonate ions. It is that hardness which can be removed by boiling.

Permanent hardness

Permanent hardness is hardness (mineral content) that cannot be removed. Ions causing permanent hardness of water can be removed using a water softener, or ion exchange resin.

Total Permanent Hardness
= Calcium Hardness + Magnesium Hardness

The calcium and magnesium hardness is the concentration of calcium and magnesium ions expressed as equivalent of calcium carbonate.

Hardness can be quantified through instrumental analysis, an individual test kit, or through the use of test strips specifically formulated for making these measurements.

1. A colorimeter passes a white light beam through an optical filter which transmits only one particular color or band of wavelengths of light to the photodetector, where it is measured. The difference in the amount of colored light transmitted by a colorless sample (blank), and the amount of colored light transmitted by a colored sample, is a measurement of the amount of colored light absorbed by the sample. In most colorimetric tests, including hardness, the amount of colored light absorbed is directly proportional to the concentration and is reported by the meter.
2. Test strips are typically produced from plastic, with chemically impregnated pads on the end. These pads are designed to react with specific ions and produce a specific color change. Once a test strip is reacted and a color is developed, the strip is then compared to a printed color chart. The color chart is specifically designed to represent color reactions at various concentrations. Matching the strip to the closest color match produces a concentration reading.

B.9 Resistivity/Conductivity

The resistivity (Ωm) of a support fluid is influenced by the dissolved salts (ppm) or (gpg, grain per gallon) in the water portion and the insoluble solid material contained in the water portion. The greater the concentration of dissolved salts, the lower resistivity of the solution. Unlike metals, the resistivity of a solution decreases as temperature increases. The resistivity is measured and controlled to permit better evaluation of formation characteristics, fluids, and filtrates. The determination of resistivity involves the measurement of resistance to the flow of electrical current through a sample of known configuration. In the direct-reading resistivity meter, the resistance measurement is converted to resistivity in ohm meters.

FIGURE B.7 ANALOGUE AND DIGITAL RESISTIVITY METERS



Evaluation of dissolved salts can alternatively be performed by measuring electrical conductivity ($\mu\text{S}/\text{cm}$ or mS/cm). The higher the salt content in the fluid the greater the conductivity value. A portable conductivity meter can be used on site to obtain a direct-reading measurement. Water obtained from seawater using the reverse osmosis process can have a conductivity from 0 to 200 $\mu\text{S}/\text{cm}$. Tap water is generally between 200 and 800 $\mu\text{S}/\text{cm}$. For seawater it is possible to get conductivities ranging from 20 to 50 mS/cm (20000 to 50000 $\mu\text{S}/\text{cm}$).

B.10 Chlorine

Usually not all chlorine exists as free chlorine. It depends how much organic matter, particularly nitrogenous organic matter, is present. The chlorine reacts with ammonia or organic amines to form chloramines. This chlorine is called combined chlorine. Chloramines have lower disinfecting power than free chlorine but have the advantage of being more persistent.

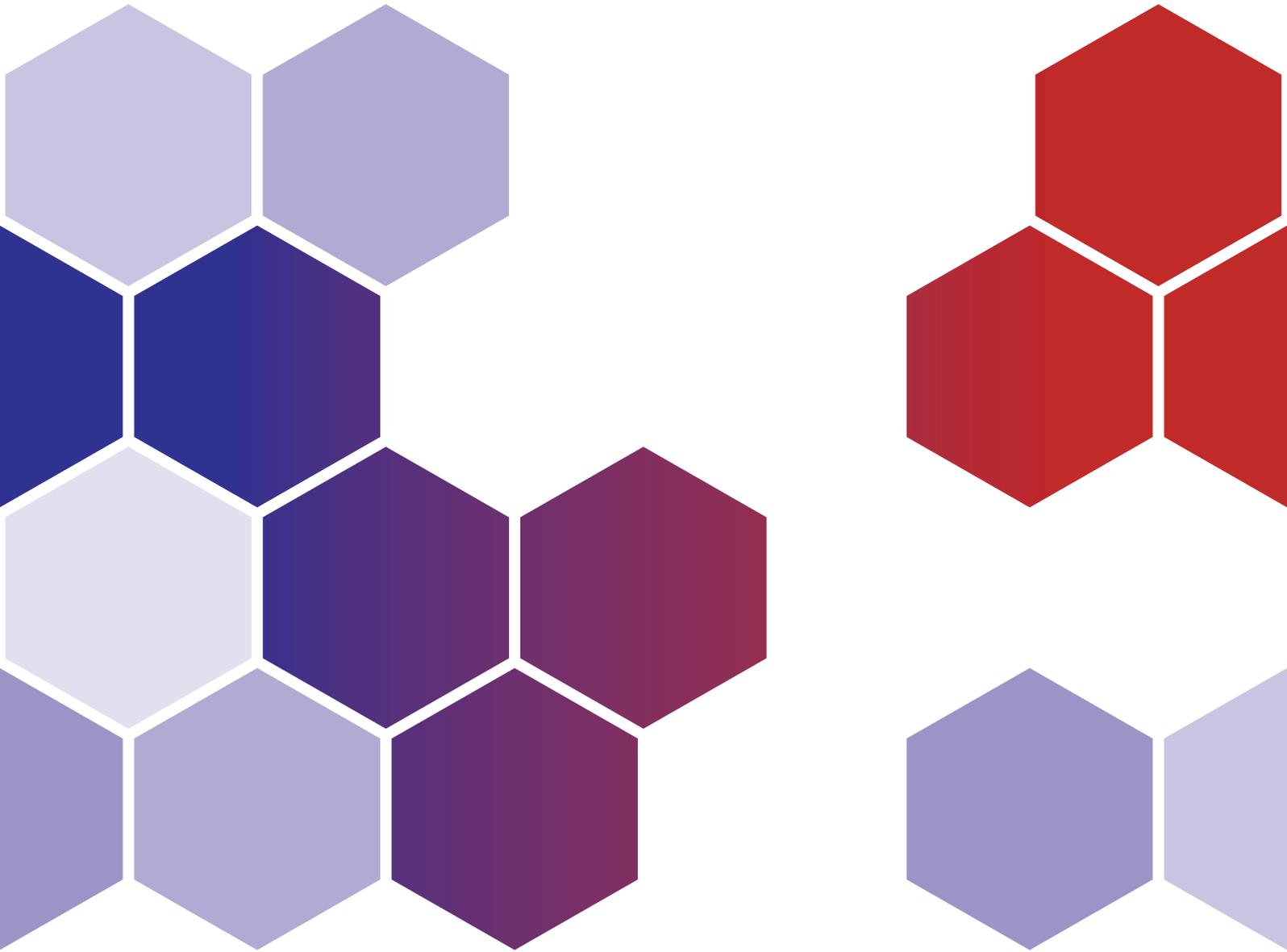
1. Titration: Iodometric method. For higher levels of chlorine an iodometric titration is sometimes used. This method tests for total chlorine. The chlorine in the test solution oxidizes some iodide that has been added. This forms an iodine complex that then reacts with an indicator like starch. The solution is titrated with a reducing agent back to a clear colour. This method is subject to interferences from other oxidizing agents that may be present apart from chlorine.
2. Test strips are typically produced from plastic, with chemically impregnated pads on the end. These pads are designed to react with specific ions and produce a specific color change. Once a test strip is reacted and a color is developed, the strip is then compared to a printed color chart. The color chart is specifically designed to represent color reactions at various concentrations. Matching the strip to the closest color match produces a concentration reading.
3. DPD method. The most common method for free chlorine is the DPD method. At near neutral pH chlorine oxidises the DPD to form a magenta coloured compound. However this method only works for low chlorine levels up to approx 10 ppm. At higher chlorine levels the reaction proceeds beyond the magenta coloured compounds with a 'bleaching out' of the deeper colour.
4. A colorimeter passes a white light beam through an optical filter which transmits only one particular color or band of wavelengths of light to the photodetector, where it is measured. The difference in the amount of colored light transmitted by a colorless sample (blank), and the amount of colored light transmitted by a colored sample, is a measurement of the amount of colored light absorbed by the sample. In most colorimetric tests, including chlorine, the amount of colored light absorbed is directly proportional to the concentration, and is reported by the meter.
5. Amperometric method: In this method, chlorine is measured by a sensor probe containing the electrolyte potassium chloride (KCl). The chlorine present in the water moves across the membrane on the bottom of the probe and reacts with the KCl to generate an electric current. The probe measures the current produced to determine the level of chlorine. The stronger the current, the higher the level will be of present chlorine.

B.11 Chloride

There are several methods for determining the chloride content.

1. Titration
 - a. (Silver Nitrate Solution)The Chloride concentration determined by titration uses a silver nitrate solution to remove the chloride from solution as AgCl in the form of a white precipitate. The endpoint of the titration is detected using a potassium chromate indicator. A potassium chromate indicator is used to react with the excess of Ag forming Ag_2CrO_4 present after all AgCl is out of solution.
 - b. (Mercurimetric Determination). In nitric solution chloride ions are titrated with mercury nitrate solution against 1,5-diphenylcarbazone as the indicator, forming slightly dissociated mercury chloride in the process. At the titration end-point, excess mercury ions react with the indicator to form a blue-violet complex. The chloride concentration is determined from the consumption of titration solution
2. Test strips are typically produced from plastic, with chemically impregnated pads on the end. These pads are designed to react with specific ions and produce a specific color change. Once a test strip is reacted and a color is developed, the strip is then compared to a printed color chart. The color chart is specifically designed to represent color reactions at various concentrations. Matching the strip to the closest color match produces a concentration reading.
3. A colorimeter passes a white light beam through an optical filter which transmits only one particular color or band of wavelengths of light to the photodetector, where it is measured. The difference in the amount of colored light transmitted by a colorless sample (blank), and the amount of colored light transmitted by a coloured sample, is a measurement of the amount of coloured light absorbed by the sample. In most colorimetric tests, including chloride, the amount of colored light absorbed is directly proportional to the concentration, and is reported by the meter.

Appendix C

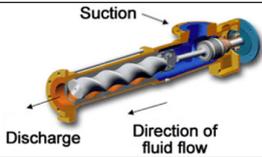
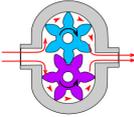
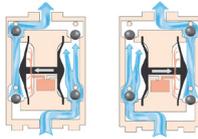
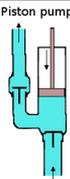
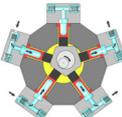
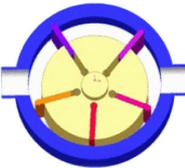
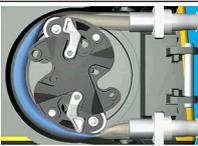


Appendix C: Types and properties of pumps

Positive displacement pumps

Positive displacement pumps draw fluid into a compartment at the inlet and move it to an outlet for discharge, most typically using a rotary, reciprocating, or diaphragm method to move fluid.

TABLE C.1 POSITIVE DISPLACEMENT PUMPS

Type of Pumps	Schematic	Brief Description
Rotary Lobe		This type of positive displacement pump based on the counter rotation of pumping elements or lobes (without making contact) within a chamber. Liquid flows into the cavity and is trapped by the lobes as they rotate. Liquid travels around the interior of the casing in the pockets between the lobes and the casing, it does not pass between the lobes. Finally, the meshing of the lobes forces liquid through the outlet port under pressure.
Progressing cavity pump		This type of positive displacement pump is also known as an eccentric screw pump or cavity pump. It has a long helical rotor sitting in a twin helix casing or stator (usually made of rubber). When the rotor is set in motion the eccentric shaft creates multiple cavities that "progress" along the stator pushing the fluid towards the discharge side.
Screw Pump		As the pump rotates, the intermeshing of the two screws along with the pump housing forms chambers. These chambers fill with the pumped fluid and move it from the suction side to the higher pressure discharge side.
Rotary Gear Pump		As the gears rotate they separate on the intake side of the pump, creating a void and suction which is filled by fluid. The fluid is carried by the gears to the discharge side of the pump, where the meshing of the gears displaces the fluid. The mechanical clearances are extremely small.
Reciprocating Diaphragm Pump		The diaphragm pump uses a combination of the reciprocating action of a diaphragm (rubber, thermoplastic, teflon) and suitable valves on either side of the diaphragm to pump a fluid.
Reciprocating Piston or Plunger Pump		This type of positive displacement pump uses the movement of a piston or plunger to vary the holding volume within a sealed chamber, thus producing a pressure differential. On the up stroke the cavity fills with the fluid sucked from an inlet, on the down stroke the fluid is ejected from the outlet. Each movement of the plunger produces a pulse. Depending on the design of the pump it may use single or multiple pistons or plungers.
Radial Piston Pump		This is a positive displacement pump with multiple pistons each with its own chamber. The pistons are organized symmetrically around an eccentric axis drive that, when put in motion, extends or retracts the pistons and draws in/displaces out the fluid from chambers.
Rotary Vane		A rotary vane pump is a positive-displacement pump that consists of vanes mounted to a rotor that rotates inside a cavity. The vanes are allowed to slide into and out of the rotor and seal on all edges, creating vane chambers that do the pumping work. On the intake side of the pump, the vane chambers are increasing in volume. On the discharge side of the pump, the vane chambers are decreasing in volume, forcing fluid out of the pump. The action of the vane drives out the same volume of fluid with each rotation.
Peristaltic		This positive displacement pump is based on using rollers on a rotating axle to compress a hose or flexible tube thus pushing the fluid along its length.
Flexible Impeller		A flexible impeller pump is a positive-displacement pump that, by deforming impeller vanes, draws the liquid into the pump housing and moves it to the discharge port with a constant flow rate. The flexibility of the vanes enables a tight seal to the internal housing, making the pump self-priming, while also permitting bi-directional operation.



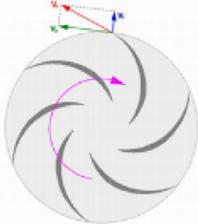
Appendix C: Types and properties of pumps

Centrifugal Pumps

Centrifugal pumps use a rotating impeller to create a vacuum in order to move fluid. The pump's impeller rotates within the housing and reduces pressure at the inlet. This motion then drives fluid to the outside of the pump's housing, which increases the pressure enough to send it out the discharge.

Axial flow centrifugal pumps have a curved propeller-shaped impeller, whereas the impeller on a radial flow centrifugal pump looks more like a fan.

TABLE C.2 CENTRIFUGAL PUMPS

Centrifugal Pump		
Centrifugal Pumps		A rotating impeller is set in a chamber. The fluid enters the chamber close to the rotating axis of the impeller and is accelerated outwards to the outlet point. The faster the impeller revolves the higher the velocity of the liquid at the vane tip and the greater the energy imparted to the liquid. These pumps are very useful for colloids as they promote faster mixing by defragmenting the particles passing. These pumps are not as suitable for polymer based fluid with long chains as the impellers work as knives cutting the chains.

Nearly all pumps fall within these two categories. However, positive displacement pumps come in a wider variety such as gear, lobe, peristaltic, screw, and many other types of pumps as described above.

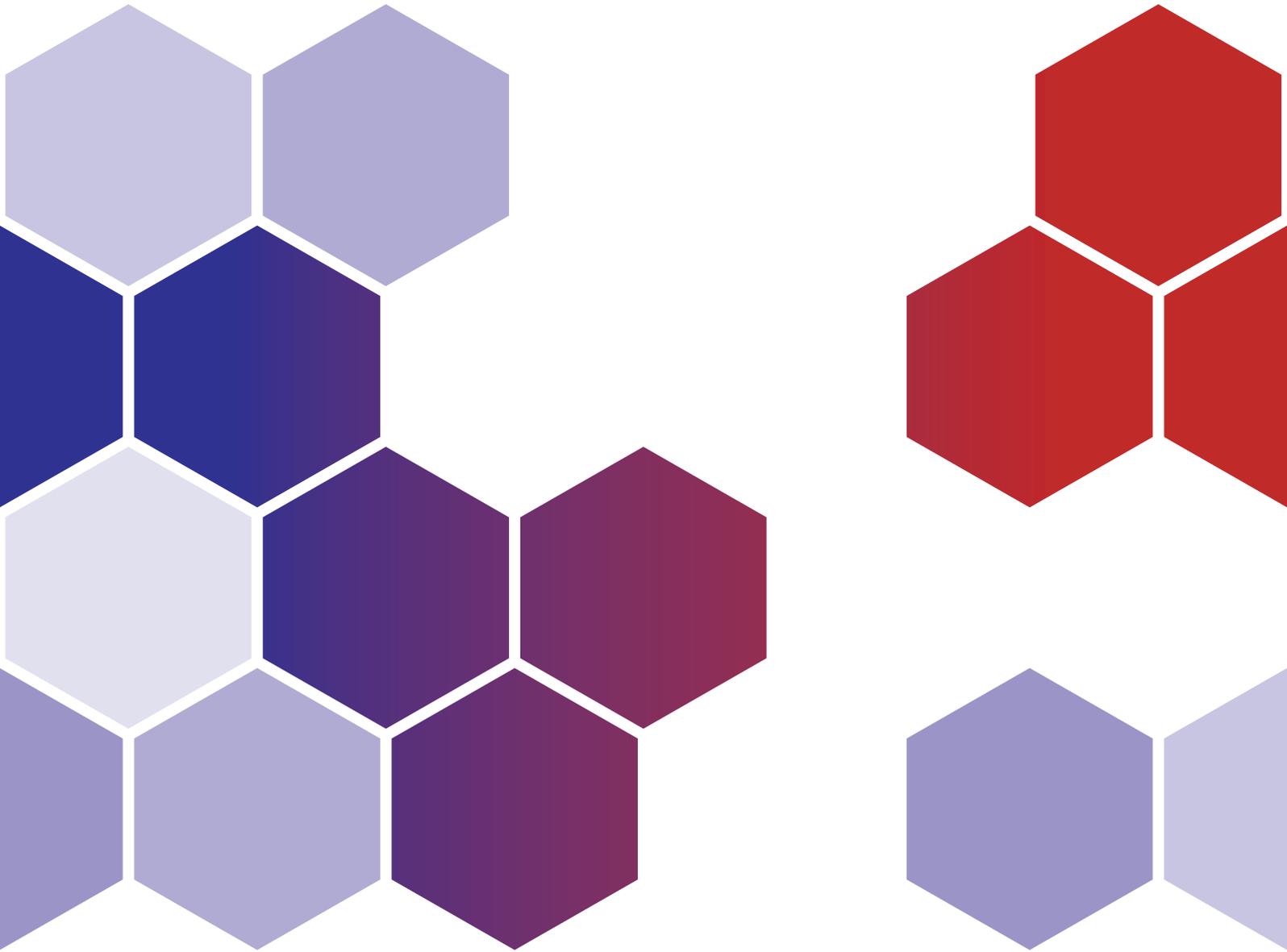
Care should be taken when using centrifugal pumps for polymer applications as the chains can be sheared by the action of the impeller.

Suppliers literature for any pumps (including pumping curves) should be consulted during the pump selection. Example curves are discussed in *Table C.3*.

TABLE C.3 A COMPARISON BETWEEN POSITIVE DISPLACEMENT AND CENTRIFUGAL PUMPS

<p>Centrifugal Pumps</p>	<p>Centrifugal pumps have varying flow depending on pressure or head, whereas the positive displacement (PD) pumps have more or less constant flow regardless of pressure.</p>	
<p>Flow rate versus viscosity</p>	<p>Another major difference between the pump types is the effect viscosity has on the capacity of the pump. The flow rate chart shows how the centrifugal pump loses flow as the viscosity goes up but the PD pump's flow actually increases. This is because the higher viscosity liquids fill the clearances of the pump causing a higher volumetric efficiency. This chart shows the effect of viscosity on the pump flow. When there is a viscosity change there is also greater line loss in the system. This means it is necessary to calculate the change in pump flow from the first chart for this pressure change.</p>	
<p>Efficiency versus pressure</p>	<p>The pumps behave very differently when considering mechanical efficiency. The efficiency chart to the right shows the impact of pressure changes on the pump's efficiency. Changes in pressure have little effect on the PD pump but a dramatic one on the centrifugal.</p>	
<p>Efficiency versus viscosity</p>	<p>Viscosity also plays an important role in pump mechanical efficiency. Because the centrifugal pump operates at motor speed, efficiency goes down as viscosity increases due to increased frictional losses within the pump. Efficiency often increases in a PD pump with increasing viscosity. Efficiency rapidly drops off for the centrifugal pump as viscosity increases.</p>	
<p>Net Positive Suction Head requirements</p>	<p>Another consideration is NPSHR. In a centrifugal pump the NPSHR varies as a function of the flow which is determined by pressure and viscosity as discussed above. As pressure and viscosity have less effect on a PD pump, NPSHR varies mainly as a function of flow which is determined by speed. The lower the speed of a PD pump the lower the NPSHR.</p>	

Appendix D



Appendix D: Sedimentation of Soil Particles in Support Fluids

This Appendix gives fuller details of the derivation of the settling velocities shown in *Table 2, Section 3.1* of the Guide. For ease of reference, this Table is reproduced below as *Table D1*.

The rate of sedimentation in a support fluid will depend on the size and shape of the particle settling and the properties of the support fluid.

The effective weight of a particle in a support fluid is given by the particle volume and density difference between the particle ρ_s and the support fluid ρ_l thus:-

$$\text{Weight in fluid} = \frac{\pi d^3 g}{6} (\rho_s - \rho_l)$$

where d is the particle diameter and g is the acceleration of gravity.

According to Stokes law the drag force D on a particle of diameter d in a Newtonian fluid (that is a fluid for which shear stress is proportional to shear rate) is given by:-

$$D = 3\pi\mu dv$$

where μ is the dynamic viscosity and v is the particle settling velocity.

By equating the weight of a particle in a fluid and the drag force, the settling velocity of particles can be assessed. *Table D1* shows examples of settling velocities of spherical particles of specific gravity 2.65 in water at 20°C (viscosity, 10^{-3} Pa s, 1 cP). For comparison, *Table D1* also shows indicative settling velocities in a 0.015 Pa s (15 cP) fluid (the apparent viscosity at high shear rates may be of the order of 0.015 Pa s for a bentonite slurry) and an example of a PHPA polymer support fluid.

TABLE D.1 ESTIMATED SPHERICAL PARTICLE SETTLING VELOCITIES IN M/HR (VALUES IN ITALICS REPRESENT REYNOLDS NUMBERS >1)

Soil type	Particle size		Settling velocity in water, viscosity 1 cP	Settling velocity in a Newtonian support fluid of viscosity 15 cP	Settling velocity in PHPA polymer support fluid
	microns	mm			
CLAY	2	0.002	<0.1	<0.1	<0.1
SILTS	6	0.006	0.12	<0.1	<0.1
	10	0.01	0.32	<0.1	<0.1
	20	0.02	1.29	<0.1	<0.1
	60	0.06	12	0.8	<0.1
SANDS	100	0.1	32	2.2	<0.1
	200	0.2	95	8.6	<0.1
	600	0.6	>200	78	4
	1000	1	>200	170	40
	2000	2	>200	>200	>200
GRAVELS	6000	6	>200	>200	>200
	10000	10	>200	>200	>200
	20000	20	>200	>200	>200

Notes to Table D1:-

Settling velocities less than 0.1 m/hr are shown as <0.1 as particles settling at velocities of 0.1 m/hr and less are unlikely to deposit any significant amount of material at the base of an excavation.

Similarly velocities >200 m/hr are shown as >200 as all particles with such velocities are likely to settle sufficiently rapidly that they are removed in normal base cleaning operations.

All diameters are Stokes diameters i.e. for non-spherical particles diameters are those of the equivalent spherical particle with the same settling velocity.

For particle settlement, Stokes law is not valid for Reynolds numbers > 0.1 though it gives reasonable results for Reynolds numbers up to 1. As the Reynolds number increases beyond 0.1, the flow regime becomes progressively more turbulent and inertial effects become progressively more important. For Reynolds numbers, $Re, > 1$, settling rates can be estimated from published drag coefficient data and are shown in italics in *Table D1*. For $Re > 1$, a drag coefficient approach has been used to develop the velocities in *Table 1*. For this the effective weight of a particle in a settling fluid is equated to the drag on the particle as follows:-

$$\frac{\pi d^3 (\rho_s - \rho_l) g}{6} = C_D \frac{\pi d^2 \rho_l v^2}{4}$$

There are a number of empirical equations for the Drag coefficient, C_D for a falling sphere, for example:

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34$$

Where the Reynolds number is:

$$Re = \frac{\rho v d}{\mu}$$

For the PHPA polymer support fluid, the fluid is assumed to be pseudoplastic and to follow the Carreau model with a consistency coefficient of 0.3 Pa s (300 cP), and a power law index of 0.3 with an upper Newtonian threshold viscosity of 19 Pa s (shear rates less than 10^{-3} s^{-1}) and a lower Newtonian plateau viscosity of 0.007 Pa s (shear rates greater than 10^3 s^{-1}). These data approximate to those for the 0.6 kg/m³ fluid shown at Page 240 of Lam and Jefferis ⁽²⁰¹⁸⁾.

For non-Newtonian fluids such as PHPA support fluids, the estimation procedure for settling velocities is subject to many uncertainties and the settling velocities given in the table should be taken only as indicators of the order of magnitude of the settling velocity.

It should be noted that many polymer systems are designed to inhibit soil dispersion. Soils excavated under such fluids may not disperse to clay and silt sizes but remain as larger cut soil lumps - at least until the polymer has penetrated into the lumps.

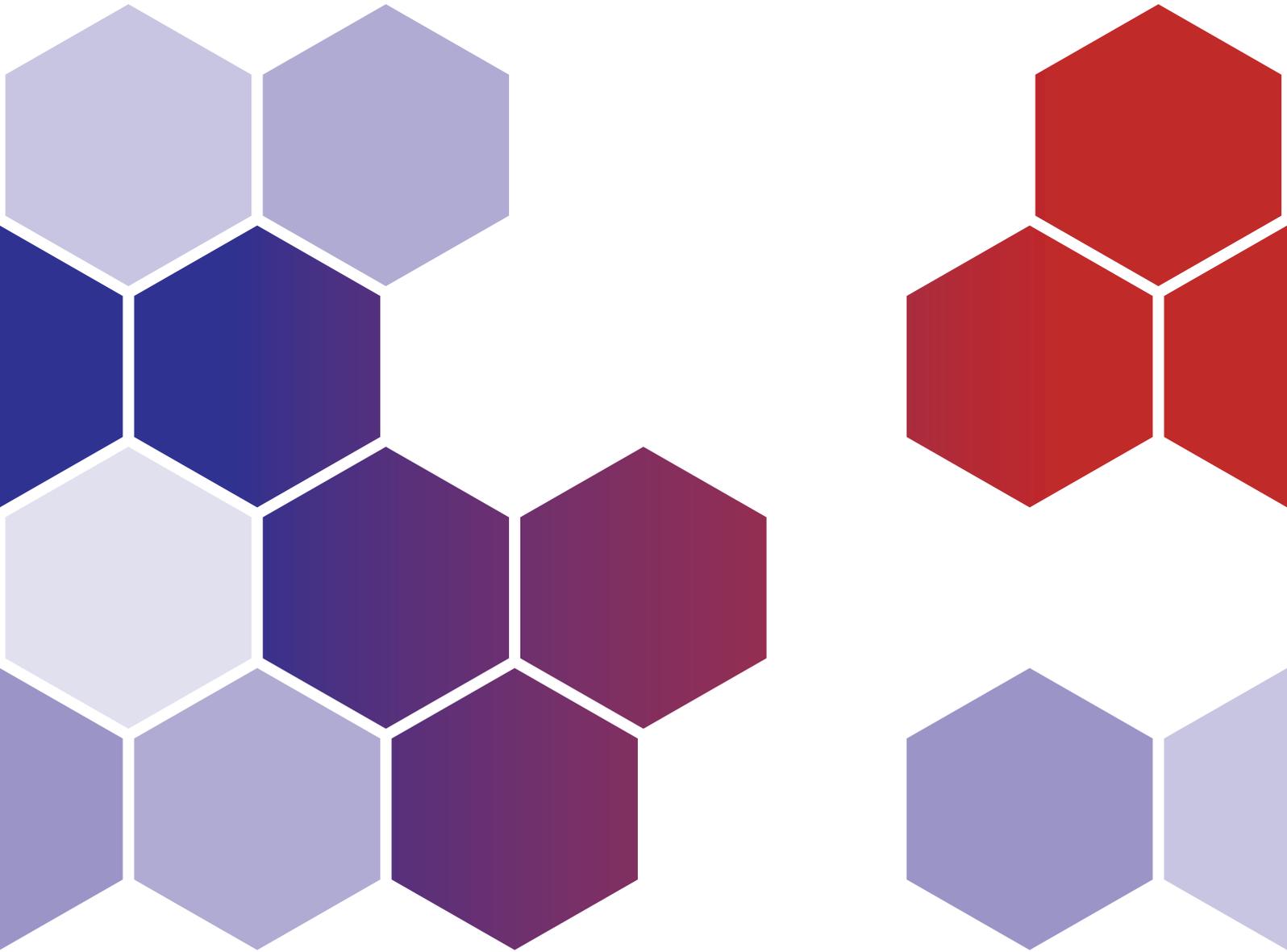
Table D1 does not give an indication of settling velocities in bentonite slurries as the properties of such fluids can vary very greatly. However, the impact of an important feature of bentonite support fluids, gelling, can be assessed. Gelling allows small particles to be held in suspension rather than settle. The minimum particle size d which will be held in a fluid of yield stress, τ , is given by Chhabra R.P. and Richardson, J.F. ⁽¹⁹⁹⁹⁾:-

$$d = \frac{\tau}{Yg (\rho_s - \rho_l)}$$

There is considerable variation in the value of Y in the literature ranging from about 0.04 to 0.2. Thus for example if the gel strength of the slurry, $\tau = 5 \text{ Pa}$, and ρ_s and ρ_l are 2650 and 1023 kg/m³ respectively, d may be in the range 1.6 to 7.8 mm and thus such particles may not settle. This can lead to a build of silts and sands in support fluids (in addition to clays). As the solids concentration increases and the suspended particles come into closer proximity, settlement will be slower than predicted by Stokes law. Also if fines are present the gel strength may increase further slowing or stopping sedimentation. These effects can lead to slurries with high and unusable viscosities and densities.

Water, sometimes used as a support fluid, has no gel resulting in fast particle settlements (see *Section 4.7* of the Guide).

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