Final Draft for Review

Best Practice Guide to Tremie Concrete for Deep Foundations

by joint EFFC/DFI Concrete Task Group

2nd Edition, 2018

Formatting notes:

1) *The designed cover shall be the same for EFFC and DFI, eg. blue and red*
2) *Place all sponsor logos as per advice from Chris Harnan*
3) *Use non-breaking blank spaces between numbers and units; and imperial follow metric numbers, in square brackets: 5 cm [2 in]*
4) *Check correct links in listed Contents, Figures and Tables*
5) *Add the Disclaimer at the bottom of the page before Terms and Definitions*
6) *In Terms and Definitions, the term shall start with a small letter, but the definition with a capital*
7) *Check symbols etc. for correct spelling*

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The contents of this guide reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. This Guide does not constitute a Standard, Specification or Regulation.

Terms and Definitions

TERMINOLOGY	DEFINITION
addition (filler and SCM: supplementary cementitious material)	Finely divided inorganic material used in concrete to improve certain properties or achieve special properties. These comprise two main types:- Type I) - inert and nearly inert (filler) e.g. lime stone powder Type II) - latent hydraulic or pozzolanic (SCM) e.g. fly ash or ground-granulated blast furnace slag.
admixture (chemical additive)	Material added during the mixing process in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete.
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. See Figure 1.
bentonite	Clay containing the mineral montmorillonite, used in support fluids, either as pure bentonite suspension or as an addition to polymer solutions.
binder (cementitious)	Inorganic material or a mixture of inorganic materials which, when mixed with water, form a paste that sets and hardens by means of hydration reactions and processes which, after hardening, retains its strength and stability even under water.
Bingham fluid model	A two parameter rheological model of a fluid with non-zero yield stress and a constant plastic viscosity.
bleeding	Form of segregation in which some of the water in the mix tends to rise to the surface of freshly placed concrete.
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. See Figure 1.
clear spacing	Minimum space between individual reinforcement bars or bundles of bars, i.e. the opening for the concrete to flow through.
consistence*	Relative mobility, or ability of freshly mixed concrete to flow i.e. an indication of workability.
cover	Distance between the outside face of the reinforcement and the nearest concrete face i.e. the exterior 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 deep foundation. See Figure 1.
durability	Ability of material (e.g. concrete) to resist weathering action, chemical attack, abrasion, and other service conditions.
fines	Sum of solid material in fresh concrete with particle sizes less than or equal to 0.125 mm.
filling ability	The ability of fresh concrete to flow and fill all spaces within the excavation, under its own weight.
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.
filtration	Mechanism of separating solids and fluid from a support fluid or from a concrete which has not yet set, where the surrounding, permeable ground under hydrostatic pressure is acting as a filter, analogous to filtration in supporting fluids.
flow retention	See workability retention.
flowability	The ease of flow of fresh concrete when unconfined by formwork and/or reinforcement.
fresh concrete	Concrete which is fully mixed, has retained flowability and is still in a condition that is capable of being placed by the chosen process. See tremie concrete.
interface layer	Material between the support fluid and the concrete, during a concrete pour, possibly accumulating and formed by material from segregated concrete and/or support fluid with soil particles.

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. See Figure 1.
passing ability	Ability of fresh concrete to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking.
paste	The part of concrete usually referred to as cement paste, consisting of fines, water, admixtures, and air, without aggregates.
plastic viscosity	Viscosity of a Bingham fluid (with non-zero shear stress).
rheology	Study of the deformation and, in particular in this Guide, the flow of a substance under the effect of an applied shear stress
robustness (of fresh concrete)	Ability of the concrete mixture to maintain the fresh properties pre- and post-casting despite minor acceptable variations in batching accuracy and raw material properties.
segregation resistance	Ability of concrete to remain homogeneous in composition while in its fresh state.
slump flow (spread)	The result of a test carried out in accordance with EN 12350-8 or ASTM C1611
slump retention	See workability retention.
specification (for concrete)	Final compilation of documented technical requirements given to the producer in terms of performance or composition.
specifier	Person or body establishing the specification for the fresh and hardened concrete.
stability	Resistance of a concrete to segregation, bleeding and filtration.
stop end (joint former)	A form, usually of steel or concrete, placed at the end(s) of a panel to create a joint; a waterbar may be incorporated at the joint.
support fluid	Fluid used during excavation to support the sides of a trench or bored pile (drilled shaft).
thixotropy	The tendency of a material to progressive loss of fluidity when allowed to rest undisturbed but to regain its fluidity when sufficient shear stress is applied.
tremie concrete	Concrete with the ability to achieve sufficient compaction by self-weight when placed by tremie pipe in a deep foundation, under submerged conditions.
tremie pipe / tremie	Segmental pipe with waterproof joints.
tremie method (submerged concrete placement or slurry displacement method)	Concrete placement method by use of a tremie pipe in order to prevent the concrete from segregation or contamination by the fluid inside the bore, where the tremie pipe – after the initial placement –remains immersed in previously placed, workable concrete until the completion of the concreting process.
viscosity	Measure of a fluid's ability to resist shear strain, specifically the resistance to flow of fresh concrete once flow has started.
workability*	The property of freshly mixed concrete which determines the ease with which it can be mixed, placed, compacted, and finished.
workability retention	Retention of specified properties of fresh concrete, such as flow and slump, for a specified duration of time.
yield stress	Shear stress required to be reached to initiate flow, also referred to as “static yield stress”.

**** Note:** Within European Standards, the word ‘consistence’ has now replaced ‘workability’ but this is not the case in the US.*

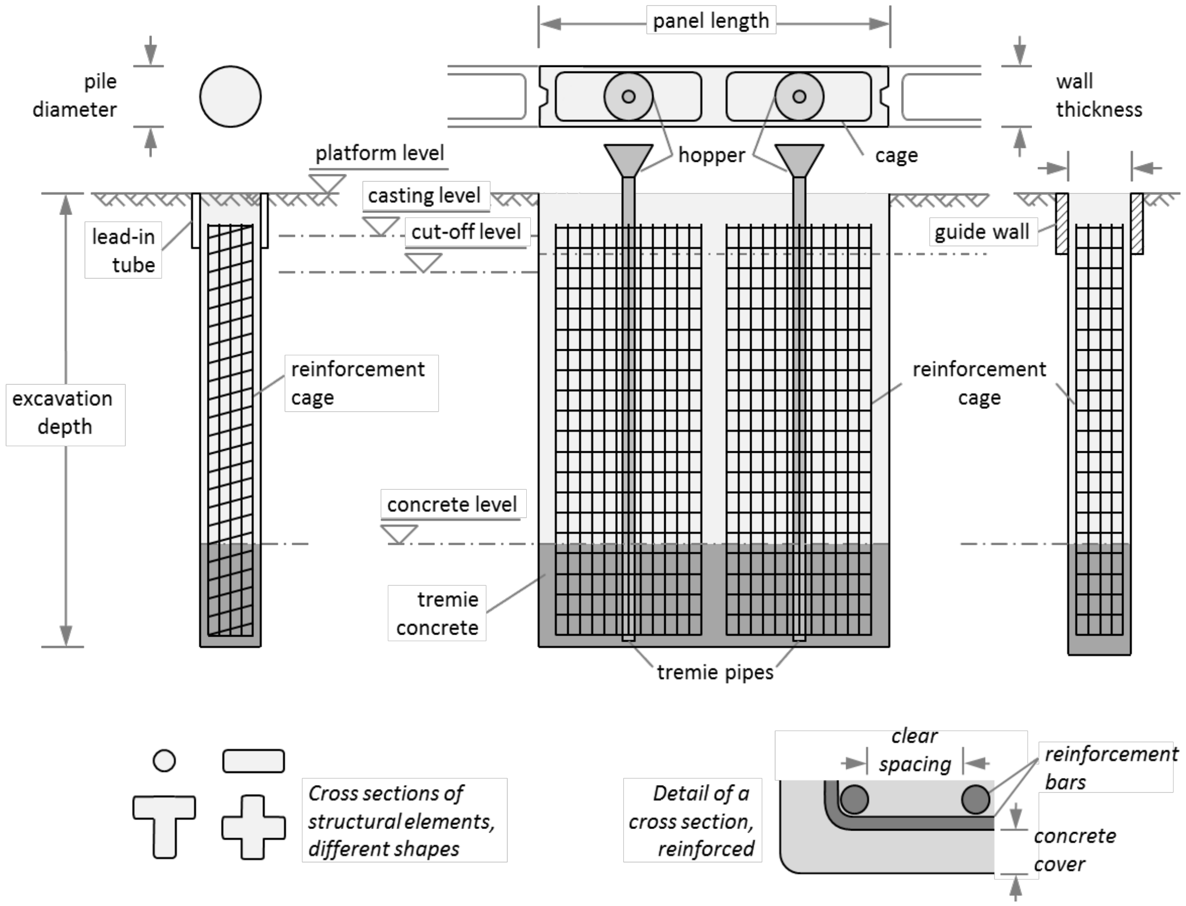
Within this Guide, the following equivalents apply:-

- *Consistence: measured from tests to EN 12350-2, -5 or -8, for Tremie Concrete, e.g. slump flow.*
- *Workability: set of fresh concrete characteristics i.e. flowing, passing and filling ability, see Figure 4, including consistence.*

List of Abbreviations and Symbols

AASHTO	American Association of State and Highway Transportation Officials
ACI	American Concrete Institute
ADSC-IAFD	The International Association of Foundation Drilling
AFNOR	Association Francaise de Normalisation
API	American Petroleum Institute
ASTM	ASTM International
CEN	European Committee for Standardisation
CIA	Concrete Institute of Australia
CIRIA	Construction Industry Research and Information Association (UK organisation)
DAfStb	Deutscher Ausschuss für Stahlbeton (German Committee for Structural Concrete)
DFI	Deep Foundations Institute
ECPC	Equivalent Concrete Performance Concept
EFFC	European Federation of Foundation Contractors
EPCC	Equivalent Performance of Combinations Concept
FHWA	Federal Highway Administration
GGBS	Ground granulated blast furnace slag
ICE	Institution of Civil Engineers (UK Professional Body)
ISO	International Organization for Standardization
ÖBV	Österreichische Bautechnik Vereinigung (en: Austrian Society for Construction Technology)
QA/QC	Quality Assurance/Quality Control
SCC	Self-Compacting Concrete
VSI	Visual Stability Index
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
η	dynamic viscosity
h_1, h_2	embedment of tremie pipe before (h1) and after (h2) 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	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 test
τ	shear stress
τ_0	yield stress
$\dot{\Upsilon}$	shear rate

Figure 1: Examples of deep foundations



1 General

1.1 Background

Concrete technology continues to advance rapidly and modern mixes with five components – cement, additions, aggregates, (chemical) admixtures and water – often have characteristics which differ significantly from the older three component mixes – cement, aggregates and water. Recent trends have favoured higher strength classes and lower water/cement ratios, resulting in greater dependence on admixtures to compensate for reduced workability and to meet the (often competing) demands for workability in the fresh state and setting time. The application of testing methods which reflect the true rheological properties of the concrete has not developed at the same rate as the mixes themselves and it is still not uncommon for the workability (e.g. measured by slump) to be used as the only property for acceptance of the fresh concrete.

A joint review of problems in bored piles and diaphragm walls cast using tremie methods by both the European Federation of Foundation Contractors (EFFC) and the Deep Foundations Institute in the United States (DFI) identified a common issue. The review determined that many of the problems were caused by (or in part due to) the use of concrete mixes with inadequate workability, or insufficient stability or robustness. It further identified the primary causes as inadequate concrete specifications and inadequate testing procedures. The consequences of these problems are often significant and it was recognised that developing suitable and robust mixes is absolutely essential, as well as appropriate testing methods to ensure compliance.

A joint Concrete Task Group was established by EFFC and DFI in 2014 to look at these issues and this Guide is the output from that Task Group.

A research and development project, funded by the Sponsors of this Guide, was carried out from 2015 to 2018 by the Technical University of Munich in conjunction with the Missouri University of Science and Technology. This project included desk studies, laboratory testing, and on-site testing at worksites in Europe and the US. Furthermore, the Task Group has reviewed and evaluated state-of-the-art computational methods to numerically simulate concrete flow in deep excavations with academic partners from universities. The results are presented in this 2nd Edition of the Guide.

1.2 Purpose and Scope

The primary purpose of this Guide is to give guidance on fresh concrete characterisation with respect to its performance, the mix design process, and the methods used to test the fresh concrete. The principles of this Guide apply to tremie concrete for deep foundations but may also be applied for other forms of deep foundations (e.g. continuous flight auger piling).

The Guide addresses design considerations including concrete rheology, mix design, reinforcement detailing, concrete cover and good practice rules for placement. A review of methods to test the as-built elements is presented together with advice on the identification and interpretation of the results.

Figure 2 summarises how the demanding and often conflicting requirements should be considered throughout the development of a concrete mix. There is a very clear potential for conflict between the parties (e.g. designer, contractor, owner, client, supplier etc.) and a risk to the quality of the works. This Guide highlights the important areas that require careful consideration in order to minimise the potential risks, including the appropriate structural detailing and the use of state-of-the-art execution methods.

Getting the mix right can only be achieved via a joint approach between the Specialist Contractor (to satisfy the execution requirements), the Designer (to meet durability and structural needs), and the Supplier (to produce an economic and practical mix).

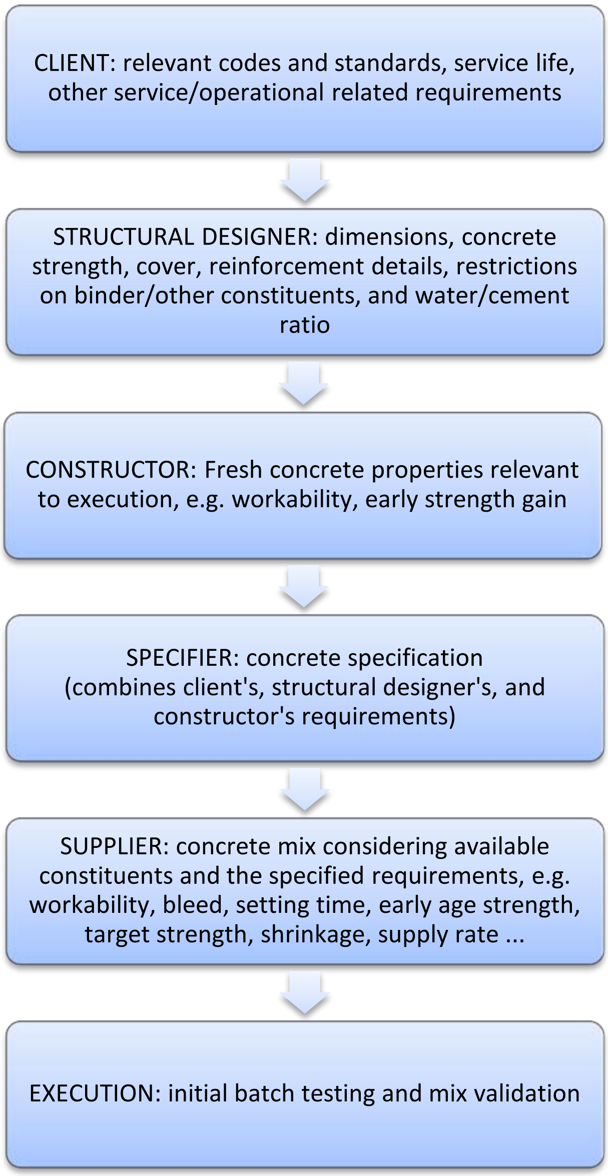
The Task Group has carried out a detailed assessment of current best practice and research. It is hoped that this Guide will provide information for use in future European and American Standards.

This 2nd edition of the Tremie Guide recommends acceptance ranges for fresh tremie concrete based on the test methods proposed. In addition, it presents details of concrete flow types based on site tests and numerical modelling studies.

The 1st Edition of the Guide contained requirements for support fluids. The support fluid has a direct impact on the quality and integrity of the final product. The concrete and the support fluid are therefore inextricably linked.

A new Support Fluid Guide covering all aspects related to support fluids is being prepared by a Task Group established in 2017 and this should be published in 2019. Requirements for support fluids have therefore been removed from this 2nd Edition of the Guide.

Figure 2: Typical evolution of concrete mixes



The Guide will assist individuals and corporations involved in the procurement, design, and construction of bored piles and diaphragm walls including Owners/Clients, Designers, General Contractors and Specialist Contractors. It is intended as a practical addition to existing standards, not a substitute. Project specifications, Standards and Codes should always take preference.

2 Design Considerations Impacting Concrete Flow

2.1 General

The design of deep foundations is a specialist subject requiring both structural and geotechnical input, as it must also consider the conditions for the execution of the deep foundation works. This section is limited to structural detailing and the impact of the reinforcement cage on the flow of the concrete through the reinforcement bars into the cover zone embedding the bars. The impact of concrete placement on end bearing and shaft friction are not considered in this Guide and reference should be made to Eurocode 7 (EN 1997-1) or relevant US standards e.g. FHWA GEC10.

With regards to the reinforcement detailing, the ideal situation for tremie concrete placement is for there to be no obstructions to concrete flow based on acceptable clearances and cover. Unfortunately the reinforcement cage represents a major obstruction to flow through the horizontal and vertical bars and around spacer blocks and box-outs (if required). The structural design, including the design of the reinforcement cage, therefore has a significant effect on the quality of the finished element.

The following sections give good practice recommendations for clear reinforcement spacing and cover. The structural engineer responsible for the reinforcement detailing should consider the requirements for successful concrete placement specific to their design as well as the minimum general requirements given in Standards i.e. the structural design must meet the needs of the designer plus the constructor in exactly the same way as the concrete mix design. This may require the designer to seek specialist advice.

2.2 Clear Reinforcement Spacing

The clear reinforcement spacing (shown as ‘a’ in Figure 3) must be assessed both on the structural requirements and the ability of the concrete to flow past the reinforcement during concreting.

According to Eurocode 2 (EN1992-1) the structurally required clear spacing between vertical bars or bundles of bars should be double their diameter D_s or nominal diameter $D_{s,n}$ (see *Table E.1* in *Appendix E*).

For execution the minimum clear spacing must respect two requirements, both with regards to the concrete. The first is to allow the concrete – understood as a Bingham fluid – to flow through the reinforcement and the second is to avoid blocking by the concrete’s aggregate:

$$a \geq \max \begin{bmatrix} \text{min a} \\ 4 \text{ x } \mathrm{D_{max}} \end{bmatrix}$$

ACI336 requires a minimum clear spacing, min a, for vertical bars of greater than or equal to 100 mm (including lap zones) or four times the maximum aggregate size, $D_{max,}$ whichever is greater. EN206, EN1536 and EN1538 mirror the ACI requirements except that they allow a reduced clear spacing on vertical bars of 80 mm at splice zones, provided that the second requirement to maximum grain size is met. These and further requirements are summarised in *Table E.1* and *Table E.2* in *Appendix E*.

In order to ensure flow of concrete into the cover zone, it is recommended that the minimum clear spacing on vertical bars is 100 mm, even in splice zones. This can be achieved either by increasing the clear spacing outside the splice zone, or using couplers, or cranking the vertical bars so that the overlap is radial from the centre of the element.

The clear spacing of the horizontal reinforcement should be considered separately as these restrict the vertical flow of the concrete.

Multiple layer reinforcement should be avoided wherever possible to reduce the risk of adverse effects on concrete flow. Multiple layers should be replaced by bar bundles, larger bar diameters or higher grade steel. If multiple layers cannot be avoided the minimum clear spacing, min a, should be increased and full scale trials are recommended.

Very high steel densities in deep foundation elements are often an indicator that the element size needs to be increased.

Note: Besides the risk reduction with regards to the quality and integrity of the final product, increased element sizes may also prove cost effective, dependent on the relative costs of the concrete and the reinforcement.

Bending tolerances for reinforcement manufacturing should also be considered within the structural design.

Note: In diaphragm wall panels and other non-symmetric situations, it may be advantageous to locally increase the clear spacing in areas where there is the greatest resistance to flow e.g. corners of cages where the distance from the tremie pipe is a maximum.

2.3 Concrete Cover

Regarding the concrete cover for deep foundations, there are two independent requirements to be considered at the design stage. The first requirement covers the need for a certain concrete cover during the structure’s service life and the second is the need for a minimum concrete cover during execution to allow for concrete flow and the removal of temporary casing. These two approaches are independent and therefore not necessarily compatible.

For both requirements, the designer should specify a nominal cover, $c_{nom,}$ based on a minimum cover, $c_{min,}$ plus an allowance for construction tolerances, Δc_{dev}, as shown in *Figure 3*.

$$\mathrm{c_{nom}} = \mathrm{c_{min}} + \Delta \mathrm{c_{dev}} \quad \text{with} \quad \mathrm{c_{min}} \geq \max \begin{bmatrix} \mathrm{c_{min,structural}} \\ \mathrm{c_{min,execution}} \end{bmatrix}$$

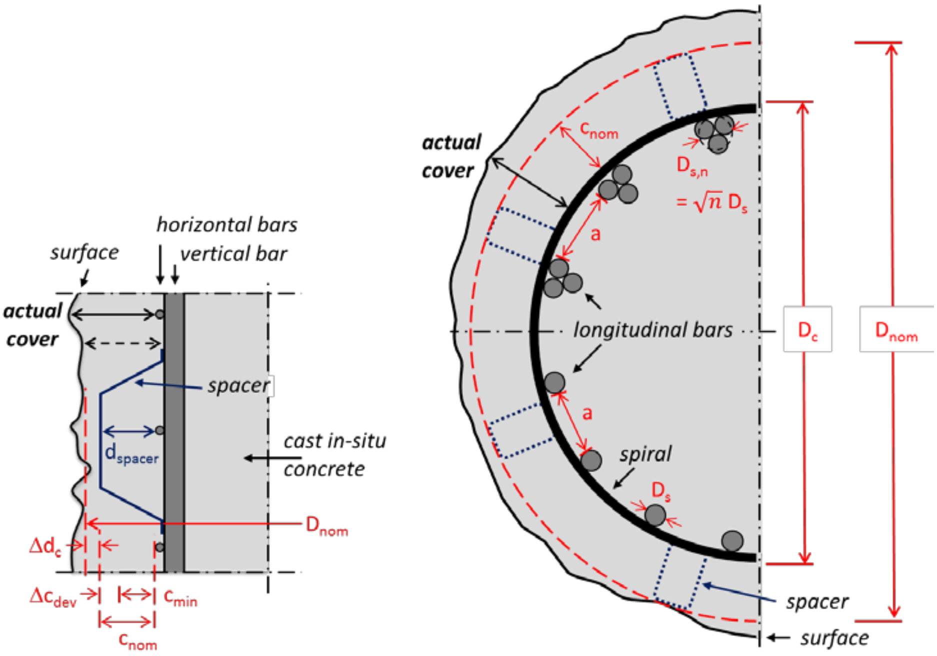
For execution, a nominal concrete cover of at least 75 mm [3 in] is recommended, which takes into account a minimum cover of 50 mm [2 in] and an allowance for construction tolerances of 25 mm [1 in]. In most cases, the minimum nominal cover for execution will exceed those derived from structural and durability requirements.

Note: In Appendix E the present variation of normative rules is discussed in detail. EN 1536 and the FHWA GEC 10 also identify particular instances where the minimum nominal cover must or should be increased.

Spacers are usually detailed to cover the design nominal cover. It should also be recognised that an additional tolerance, $\Delta d_{c,}$ should be considered in the cage design to allow the installation of the cage into the excavation (see *Figure 3*):

$$\mathrm{D_c} = \mathrm{D_{nom}} - 2\,\mathrm{c_{nom}} - 2\,\Delta \mathrm{d_c}$$

Figure 3: Concrete cover and bar spacing in deep foundations



Note: The specific case of a bored pile constructed using a temporary casing is shown and discussed in Appendix E.

3 Properties of Tremie Concrete

3.1 General

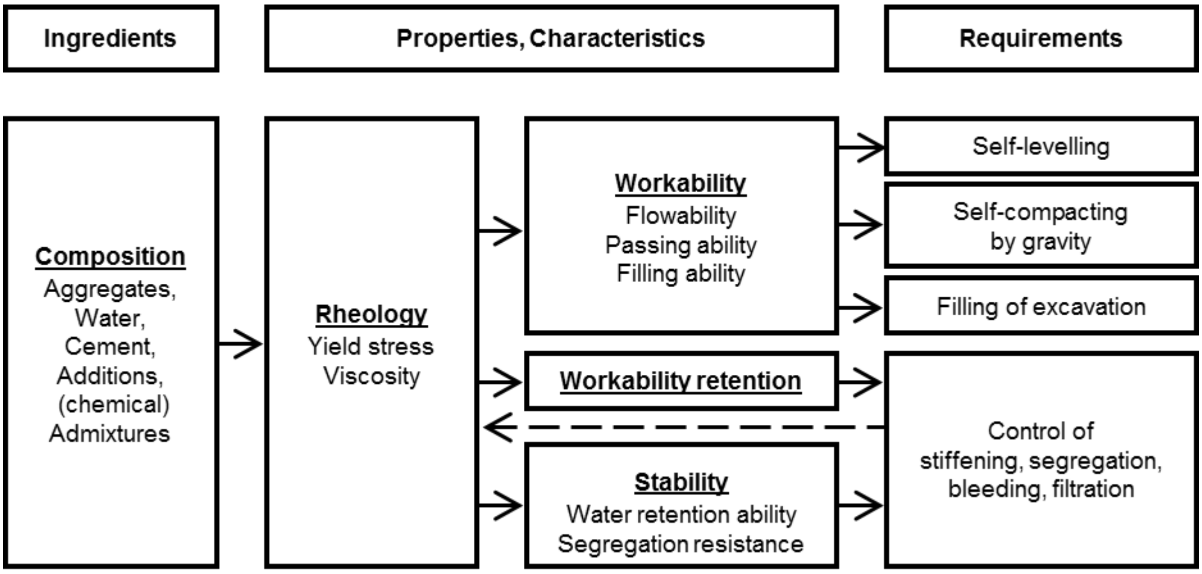
Rheology is the study of the deformation and the flow of a substance under the effect of an applied shear stress. The rheology of concrete is fundamental to its behaviour during casting. Rheology determines the success of placement and the quality of the final product e.g. durability is a direct function of rheology.

The key rheological characteristics for fresh concrete are:-

- Workability (the general term defining the ability of the concrete to fill the excavation, self-level and self-compact by gravity)
- Workability retention (defining how long the specified fresh properties will be retained)
- Stability (resistance to segregation, bleeding and filtration)

Over recent decades, concrete as a material has evolved significantly. Concrete designs normally include durability requirements in addition to strength parameters and as durability and strength are, for a given mix of materials, directly related to each other, there is a tendency to specify higher strength classes and lower water/cement ratios. This results in greater dependence on chemical admixtures to compensate for the reduced water content, the associated reduction in workability, and to meet the often competing specification demands for workability, stability, and flow retention. insufficient stability or flow retention can affect the workability. The relationship between ingredients, fundamental rheological properties, general concrete characteristics and performance requirements is illustrated in *Figure 4.*

Figure 4: Dependencies between composition, rheology and related characteristics, and overall requirements



There is very little guidance in current standards on the assessment of rheological behaviour. This chapter provides an explanation of concrete rheology and key parameters used to identify rheology.

3.2 Rheology and Workability

To properly understand the behaviour of concrete in a fresh state, it is useful to consider it as a Bingham fluid model with the two parameters:

- Yield stress, τ_0
- Plastic viscosity, μ

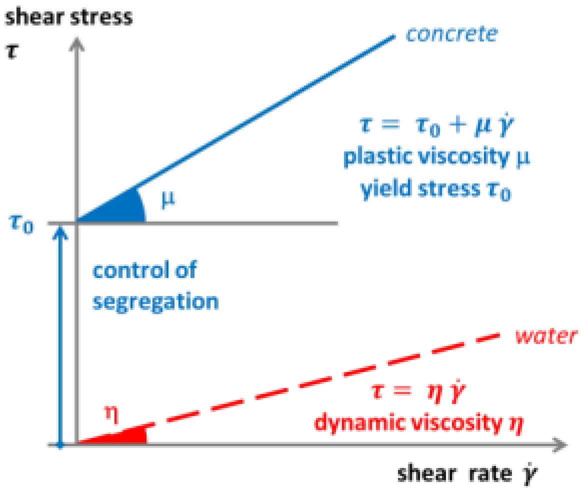
Yield stress is the shear stress required to be reached to initiate the flow of concrete. To control segregation the yield stress must not be too low. Conversely, to allow concrete to consolidate under gravity (without external vibration) the yield stress must not be too high.

Plastic viscosity is the slope of a Bingham fluid plot, as shown in Figure 5, and is a measure of its resistance to flow. It is related to the granular interaction and the viscosity of the paste between grains. Successful placing of concrete requires low viscosity as this affects its distribution inside the excavation and also the time required to empty a ready-mix truck.

In practice, both yield stress and plastic viscosity will be time and shear history dependent.

Figure 5 demonstrates that concrete requires a certain amount of energy to start moving (the yield stress) and, thereafter, it resists this movement (by viscosity).

Figure 5: Plastic behaviour of a Bingham fluid (e.g. concrete) and a Newtonian fluid (e.g. water)



Individual practical tests on the properties of fresh concrete currently used for conformity testing and control are unable to differentiate between the key rheological parameters (yield stress and plastic viscosity), which can only be determined with specialist laboratory apparatus (e.g.concrete rheometer). Until now, the ease of flow, as a measure for viscosity, has been assessed intuitively and qualitatively during placement, for example, by observing and classifying the difficulty of emptying the tremie pipes or the ready-mix truck unloading times.

Note 1: In this Guide, both the dynamic viscosity and the plastic viscosity of a Bingham fluid are referred to using the general term ‘viscosity’.

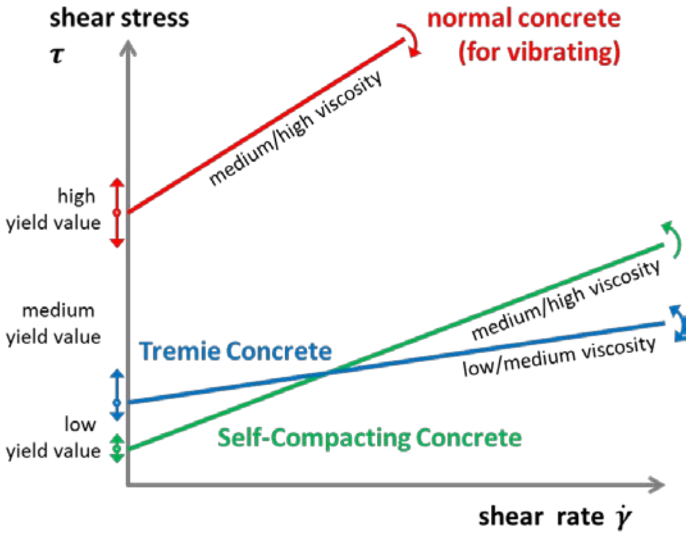
Note 2: The R&D program on rheology on Tremie Concrete in Europe and the US (Kraenkel and Gehlen, 2018) has proven a clear correlation between yield stress and plastic viscosity, evaluated by rheometer measurements, and values derived from simple and practical test methods. (See section 5.2).

Figure 6 illustrates a qualitative comparison of rheology, represented by yield stress and viscosity, for different types of concrete and applications.

Normal concrete, compacted using mechanical means, has a relatively high yield stress whereas self-compacting concrete requires very low yield stress to achieve the requirement for self-levelling and compacting by self-weight alone. The yield stress of tremie concrete lies between the two and needs to be balanced between the relatively low yield stress required for a good filling ability, and the higher stress required to displace the support fluid and control segregation in deep foundations. The large concrete head, which exists during placement in deep foundations, assists in compaction and makes it unnecessary to work with very low yield stress values which might result in sensitive concrete mixes.

Viscosity may vary widely due to the actual concrete composition. In general terms viscosity should be low for tremie concrete. This serves both to improve the ease with which concrete can flow around the reinforcement and other obstructions, and also reduces the time needed to complete a pour. In addition to general programme benefits, minimising pour durations avoids, or reduces as far as possible, the need for extended workability retention and any subsequent risk of increased mix sensitivity.

Figure 6: Qualitative comparison of rheology for different types of concrete

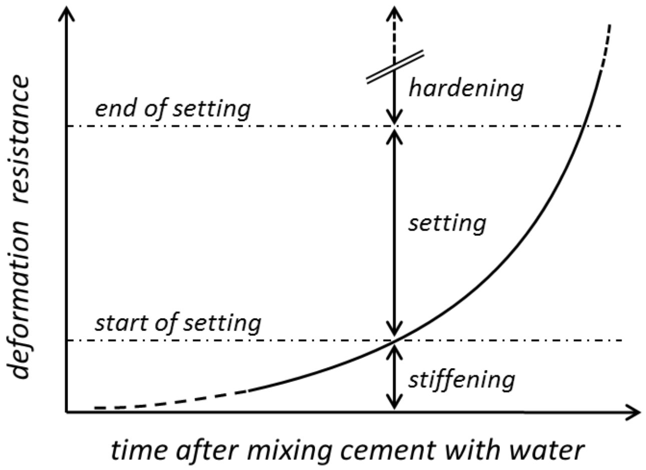


Concrete in the fresh state is considered a thixotropic material and it exhibits a form of stiffening which is reversible and fluidity is regained when the material is agitated. This behaviour is caused by the settling and packing of particles when the concrete is at rest, and the consequent break-down of this structure when a shear stress is applied.

It is important that concrete thixotropy is controlled as excessive thixotropy could adversely affect concrete flow behaviour on resumption of concreting following a short interruption. There are currently no recognised measures or acceptance criteria. A practical measure could be to limit yield stress following a specified resting time.

It is important to recognise that there is a point in time beyond which concrete should not be agitated further as the stiffening is now due, primarily, to the hydration of cement and is irreversible (Roussel, 2012). This is illustrated in *Figure 7*.

Figure 7: Stiffening and setting time



3.3 Concrete Stability

Concrete stability is defined as its ability to retain water (filtration and bleed) and resistance to static segregation. The need to control stability should be balanced against requirements for workability.

Once the concrete is placed the strain rate drops to zero. It still retains its fresh rheological properties such as its yield stress but these will change over time e.g. due to the reduction of effect with time of the workability retainer. Filtration, bleed and static segregation can all continue whilst the concrete stiffens (see *Figures 7 and 13)*. This is significant for concrete with longer setting times, especially concrete mixes for large pours with long workability retention.

Concrete stability can directly affect the quality and integrity of the final product, but also indirectly by impacting concrete flow mechanisms. Where concrete rheological properties have been affected by excessive filtration or bleed and the concrete is still required to move i.e. being displaced by later poured concrete it will affect the actual flow mechanism (see *Figure 4*).

There are two mechanisms for water loss from fresh concrete which can be broadly described as follows:-

- Filtration: separation of water from concrete due to ‘squeezing’ of concrete under applied pressure
- Bleed: gravitationally driven separation of water from cement paste and aggregate matrix.

In practice some water loss from fresh concrete will always occur and is likely to be as a result of a combination of these mechanisms. Given that segregation cannot be totally eliminated, it is essential to understand both mechanisms in order to balance stability issues with workability. Further detail on filtration, bleed and static segregation are provided below.

Filtration

Fresh concrete in deep foundations is subject to high head pressures which in turn lead to high pore-water pressures in the fresh concrete, increasing with depth. These concrete pore-water pressures can be much higher than the water pressures in the surrounding ground. A hydraulic gradient develops and this leads to water flow out of the concrete. The effect of this water loss is to stiffen the concrete i.e. to change the rheological properties to higher yield stress and higher viscosity.

Water loss due to filtration can be relevant (e.g. in very deep foundations) where a reinforcement cage or plunge column has to be inserted after concreting is complete. Water loss may stop when the concrete has stiffened due to filtration in the location of permeable soil strata. In these cases, filtration should be considered in the concrete design process.

Note: From recent R & D (Azzi, 2016 and Mohamman Dairu et al, 2015) it is believed that the filtration loss can be used as an indication of the total bleeding potential (see section on Bleeding below). Further work is required to validate and define the boundary conditions (e.g degree of consolidation in the concrete and type of filter cake).

Appendix A provides information on testing the filtration of fresh concrete. Section 5.2 recommends criteria for acceptance where relevant.

Bleeding

Bleeding of fresh concrete is a special form of segregation that occurs once the concrete has come to rest. Differences in specific gravity result in high water pressures in the fresh concrete which exceed the hydrostatic water pressures. This leads to a vertical hydraulic gradient which tends to make the water in the cement paste flow vertically towards the concrete surface. Preferential water flow pathways can also develop in concrete, often varying in size and frequency, depending on various parameters.

Note 1: Visible water flow pathways are often referred to as bleed channels (see Appendix D).

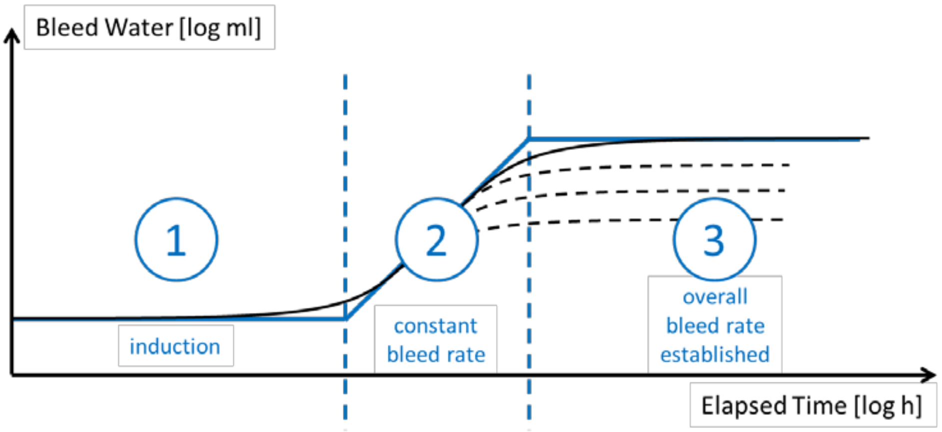
Note 2: The flow velocities in water pathways or bleed channels can be sufficient to transport fine grained aggregate and cement paste.

In order to limit the risk of anomalies created by the effects described above, bleeding should be controlled.

Recent research work (Massoussi et al, 2017) has identified the following three stages (see *Figure 8)*:-

- An induction period
- A period of constant bleed rate
- A period where overall bleed rate is established

Figure 8: Conceptual diagram on the bleeding process in cement pastes (based on Massoussi et al, 2017), with possible interruption of bleeding due to stiffening



The extent to which bleeding will occur in deep foundations depends on many factors including, but not limited to, the water to fines content, the aggregate gradation, the total concrete height and the time when the concrete reaches final consolidation.

Note 1: Concrete may not reach its final consolidated state if bleeding is stopped by stiffening of the concrete before all potential bleed water has been expelled. A distinction therefore can be made between potential bleed and bleed which is realised under any particular drainage conditions.

Note 2: Bleed water might be (partially) re-absorbed due to hydration of the cement.

Note 3: Small-scale bleeding tests cannot be directly related to the full-scale processes in deep foundations.

Appendix A provides information on testing for bleeding of fresh concrete, and Section 5.2 recommends criteria for acceptance where relevant.

While bleeding is a fundamental concrete characteristic, it is bleeding under very high concrete pressure heads that is of most relevance to tremie concretes. This results in large water pressures in the concrete, which are significantly greater than the hydrostatic water pressure. Therefore, when bleed tests are considered necessary as part of the suitability testing both bleed and filtration (under pressure) should be tested.

Segregation

Fresh concrete in deep foundations relies on its yield strength to maintain its stability once it is placed. In concrete with relatively low yield stress the relatively dense and large aggregate particles may sink through the lighter cement paste. This leads to a gradation of materials in the concrete. This process is known as static segregation.

Note 1: Case histories of static segregation are provided by Thorp et al (2018), where a heavily retarded concrete mix (delayed setting time) was evaluated for its static segregation after hardening (see Remarks in A.7).

Note 2: There may also be segregation due to dynamic effects during transport and placement. Dynamic segregation is the mechanism where the concrete mix loses its homogeneity. In turn, a sufficient resistance to dynamic effects is considered to be covered by an appropriate composition and cohesion of the tremie concrete.

Appendix A provides information on testing the static segregation of fresh concrete, and Section 5.2 recommends criteria for acceptance where relevant.

4 Mix Design

4.1 Introduction

It is not within the scope of this Guide to discuss the general principles of mix design and proportioning of materials. The reader should refer to one of the standard texts for a comprehensive coverage of relevant issues e.g. 'Concrete Technology' by Neville and Brooks (2010).

Typical steps in developing a concrete mix design are as follows:-

1) Starting from the required characteristic mechanical property, usually unconfined compressive strength (UCS), defining the average UCS, based on statistical considerations (previous experience and expected standard deviation).
2) Selecting the maximum aggregate diameter, based on reinforcement spacing (and other provisions in place). With regards to detailing (clear spacings between bars, cover etc.) reviewing the proportioning with special focus on suitable workability.
3) Proportioning of binder components based on strength and durability requirements. Considering replacement of cement by additions for limiting the heat of hydration and the thermal gradients in large structural elements, and/or for economic reasons.
4) Selecting the water/cement ratio, based on structural and durability requirements.
5) Selecting the necessary workability, based on the method of concrete placement.
6) Estimating the necessary quantity of mixing water, based on workability, maximum grain size and shape of aggregate, air content (if required), and use of water reducing admixture.
7) Computing the necessary weight of binder, based on selected w/b and necessary mixing water.
8) Calculating the total amount of aggregates, by differential volume, and their grading, based on sand fineness.
9) Evaluating the type and amount of admixture to be added, to regulate the concrete workability time, depending on temperature and total time required for delivery and placement.
10) Evaluating the type and amount of other admixtures to be added, to adjust (rheological) fresh concrete performance and/or other characteristics.

The comments made in sections 4.2, 4.3 and 4.4 are intended to highlight critical issues relevant to tremie concrete.

4.2 Mix Design Considerations

A successful concrete mix design must meet the properties of fresh and hardened concrete and be practically achievable i.e. can be achieved economically, usually with locally available materials though it should be remembered that using a more expensive aggregate with a better grading may result in greater savings because the amount of cement can potentially be reduced.

Mix design is a complex process, which shall balance the requirements of the specification with concrete performance. The detailed process for mix constituent selection and proportioning of a mix and final mix validation should consider the following:-

- Concrete specification
- Material availability, variability and economics
- Mixing plant efficiency and control capability of the production plant
- Ambient conditions expected at time of concrete placement
- Logistics of concrete production, delivery, and placement

Subsequent to the above assessment the initial selection of constituents and tentative proportioning should consider the following:-

- Compressive strength and durability (and any other design properties)
- Sufficient workability and workability time / retention
- Mix stability (resistance to segregation including bleed)
- Aggregate source, maximum size, shape (crushed or rounded) and grading
- Cement content and composition
- Use of additions and their combinations (see Appendix B for concepts for Type II additions)
- Free water content
- Water/cement ratio
- Suitable admixtures
- Sensitivity of the mix to variations in the constituents (i.e. its reproducibility in normal production)

Other design properties can result out of an extraordinary demand on durability, perhaps from a specific Service Life Design study. Particular requirements then have to be taken into account e.g. a limited chloride diffusion coefficient. A subsequent demand for special constituents, higher dosages of super-fine additions, an extra low water/cement ratio or similar, will in turn affect the fresh concrete properties. Conflicting requirements for durability and execution have to be balanced through the mix design process.

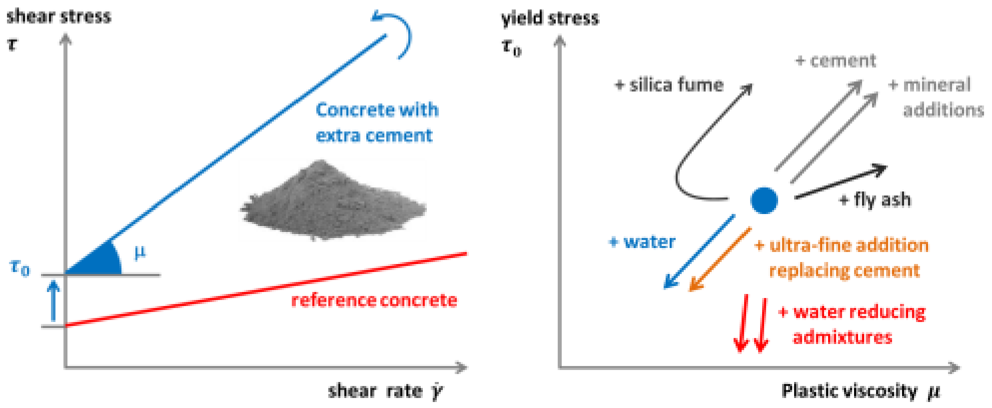
Mix design development will start in the laboratory and following satisfactory laboratory trials and sensitivity studies will move to the field for full scale trials and development, and final approval by all relevant parties, including the determination of acceptance criteria for on-site testing.

4.3 Materials

Concrete rheology is affected by all constituents and their proportioning, in particular by aggregate properties, particle shape and size distribution, cement and addition type and content, water/cement ratio and admixture types and doses.

The influence of cementitious additions on the rheological behaviour of concrete is shown on the left in *Figure 9,* leading to a higher yield stress, and to a higher viscosity. The influence of various concrete components on both yield stress and viscosity is illustrated in a rheograph to the right in *Figure 9.*

Figure 9: Influence of cement and other components on rheology (based on Wallevik, 2003)



A concrete mix shall comply with the requirements of standards and specifications applicable to the project, and must remain within the acceptable range dictated by the specified w/c-ratio, fines content, minimum compressive strength etc.

In order to obtain a more workable concrete mix i.e. to decrease the viscosity and/or the yield stress, suitable measures can be:-

- Increasing the water quantity.
- Replacing the cement partly with ultra-fine additions (significantly finer than the cement).
- Adding water reducing admixtures (plasticiser or super-plasticiser).

  Note: It is good practice to limit the percentage of water reducing admixtures in order to avoid excessive sensitivity to small variations in water content or other constituents e.g. sand, which in turn may lead to insufficient robustness of the concrete mix.

In order to obtain a more stable concrete mix i.e. to increase the viscosity and/or yield stress which would reduce a concrete's tendency to static segregation and bleeding, suitable measures can be:-

- Reducing water quantity and/or adding cement or filler, e.g. lime stone powder.
- Adding fly ash, which generally has greater influence on viscosity than on yield stress.
- Adding a viscosity modifying admixture.

  Note: Silica fume can play a special role in that it is sometimes specified to achieve high performance such as extra durability. Up to a small percentage, silica fume may have a positive effect on workability (like ultra-fine filler) but the concrete will become more viscous and reach a higher yield stress at higher percentages i.e. silica fume can also have an adverse effect and reduce workability.

Selection and assessment of aggregate grading is an important element of concrete mix design, where grading is simply the division of an aggregate into fractions, each fraction consisting of one class of particle sizes. To minimise the risk or tendency for segregation, aggregates should be well graded (e.g. Dreux and Festa, 1998).

Figure 10 contains the particle gradation curve for a maximum aggregate size of 16 mm used in the concrete mixes investigated in the field and in the laboratory, within the R&D program on rheology (Kraenkel, 2018). *Figure 11* illustrates a particle gradation curve for a maximum aggregate size of 19 mm [3/4 in] used for a field trial tremie concrete mix in the US (Kraenkel, 2018).

Figure 10: Grading curve of the concrete mixes used for the R&D program on rheology at the Technical University of Munich (Kraenkel, 2018), for the laboratory test program and in the field

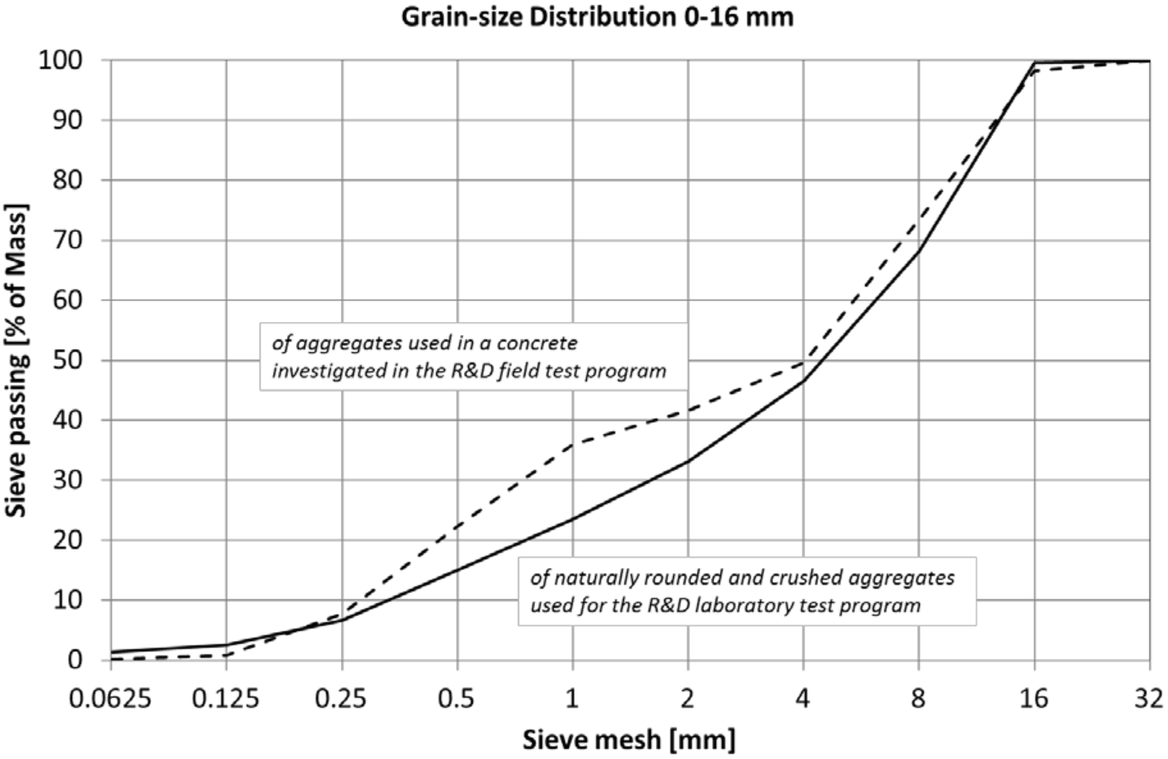
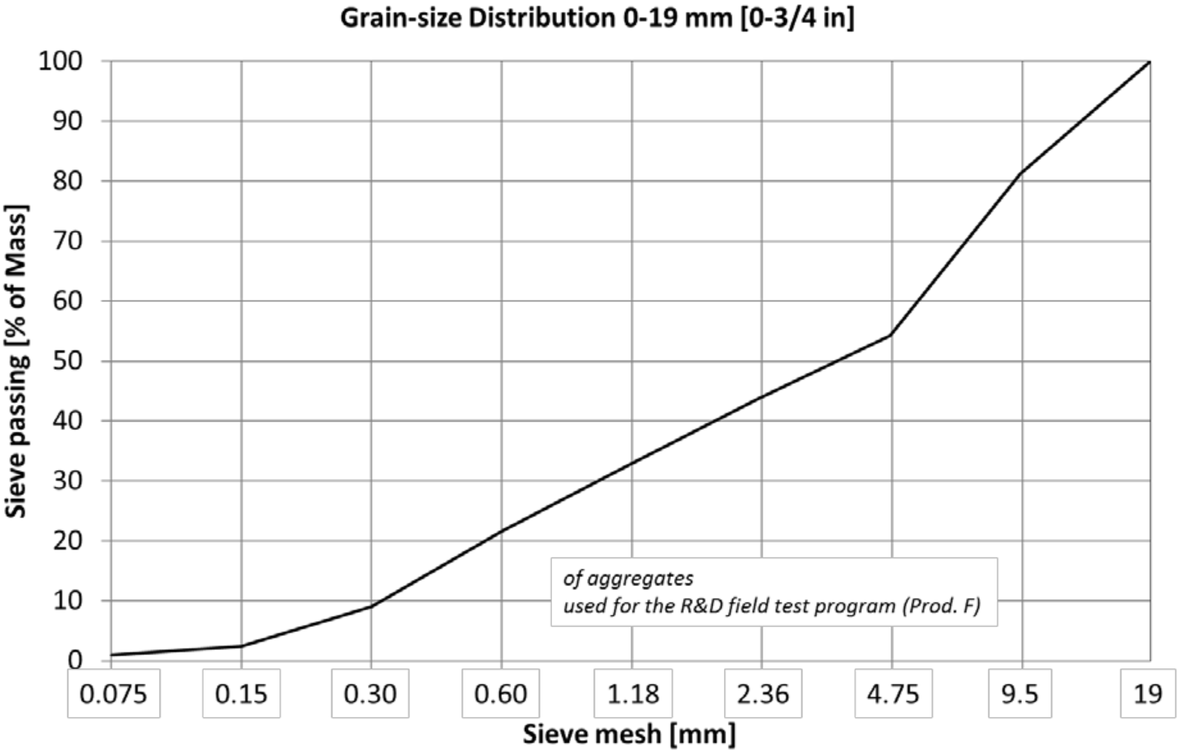


Figure 11: Grading curve of a concrete mix used for the R&D program on rheology in a field trial in the US (Kraenkel, 2018)



In developing an appropriate grading, a number of factors should be balanced:-

- The shape of the aggregate: (naturally) round shape supports the production of flowing concretes better than the more angular shape of crushed aggregate.
  Note: At the same grading and volume, the blocking resistance at reinforcement is considered higher for concrete with crushed aggregate, so that usually more (stable) paste is required for concrete using crushed aggregate.
- The size of the aggregate: a coarser grading (i.e. a higher proportion of larger aggregates) can give better workability but will also be more prone to segregation.
- The proportion of fine material: a higher proportion of fine material will give a more cohesive mix.

  Note: An excessive amount of fines might compromise workability due to its high water demand and may lead to higher required admixture dosages.

Whilst the beneficial effect of modern admixtures in the production of advanced concrete is recognised, the possible negative effect of admixtures should be understood. Reducing the quantity of water, by using water reducing admixtures, could in turn increase the viscosity. More paste might be needed to compensate for reduced workability. As a result of this, the yield stress of the bulk concrete will be reduced and the tendency for segregation increased.

In addition to the dosage of admixtures, their nature and operating mechanism can give rise to side effects such as a sticky appearance (high viscosity) or stiffening. Some combinations of cements and admixtures can cause a lack of robustness in fresh concrete, which could lead to excessive segregation (Aitcin and Flatt, 2015).

4.4 Proportioning and Practical Considerations

Mix limiting values should comply with European standard EN 206:2013 and with Annex D in particular where the requirements of EN 1536 or EN 1538 have merged, or with the relevant local Standards or other standards specified for the project.

Due to new developments or specific work conditions deviation from these standards may be considered; such as partial replacement of cement e.g. by fly ash or even the use of a lower cement content than the limiting value. Three concepts are available for the use and application of Type II additions or approved procedures for acknowledgment of equivalent performance (as described in *Appendix B*). These are:-

1) The k-value concept.
2) Equivalent concrete performance concept.
3) The equivalent performance of combinations concept.

Following initial development in the laboratory (suitability testing) the mix should be trial tested and fine-tuned using full size field batches from the supplier (part of conformity testing).

The field batch testing and evaluation should be carried out or supported by qualified personnel. Care should be taken to verify that the conditions that existed during field batching continue to exist during construction. If conditions change (aggregate source, cement source, type or dosage of additions, chemical admixture, etc.), new trial mix studies should be conducted to ensure that the target properties and performance will continue to be achieved (FHWA GEC10).

The required dosage of admixture should be determined by field batches where the conditions (ambient temperature, delivery times, placement techniques, etc.) expected during construction are replicated, and a sample of concrete is retained and tested to determine its workability retention characteristics. This trial-mixture study should also include workability testing to develop a graph of workability loss versus time after batching.

Potential problems should be recognised when improper dosages of chemical admixtures (for example over-dosing of super-plasticiser which can lead to mix instability) are used or when the effect of warm weather conditions have not been adjusted for. Without the adjustment of the dosages of retarding chemical admixtures, an increase in temperature of about 10 °C [18 °F] will increase the rate of slump loss by a factor of approximately 2, which means that a slump loss graph made in the laboratory at 22 °C [72 °F] will be very misleading for concrete being placed in the field at higher temperatures of 32 °C [90 °F] (Tuthill, 1960).

It is common practice to adopt summer and winter mixes with different doses of admixtures and minor adjustments to the cement content and w/c ratio.

Special attention should be paid to the type of mixing procedure at the concrete batching plant. In general, the wet mixing process is preferred over the dry mixing process. In the dry mixing process the dry solid components are usually weighed, mixed and batched into the truck’s mixing drum where water is added and the concrete finally mixed. Such concrete mixes tend to lack consistency in their fresh concrete properties and a wider scattering in actual water contents. It is recommended that detailed batch records with actual mixing time and quantities per truck load are obtained.

The process required to produce robust concrete mixes meeting the varied requirements of the specification for the properties of fresh and hardened concrete is complex. Testing of trial mixes in laboratory scale or, even better, in full size batches should therefore include predictable changes in mix proportioning. Applicable test methods to characterise rheology including recommended ranges for acceptance values are given in *Section 5*.

5 Specifying and Testing of Concrete, and Quality Control of Concrete Production

5.1 A New Approach to Specifying Fresh Concrete

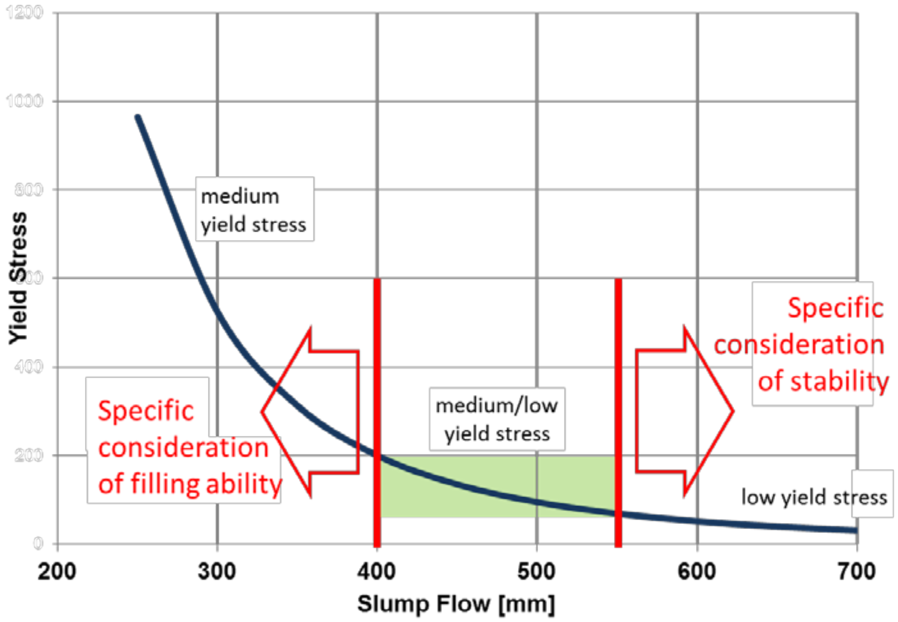
It is critical that the rheological properties of the tremie concrete are specified for the reasons described in *Section 3.* These properties should be established through mix design development and rigorous suitability trials and then appropriate conformity and acceptance testing to ensure that these properties are maintained throughout a project.

Current standard practice is to specify compressive strength, minimum cement content, maximum water/cement ratio, and slump or flow. These parameters are often insufficient to describe fully the required fresh properties for tremie concrete, particularly in terms of workability, workability retention and stability.

Additional tests are recommended as part of the mix design process to adequately assess the rheological properties in relation to appropriate criteria and a description of these tests is contained in *Appendix A.*

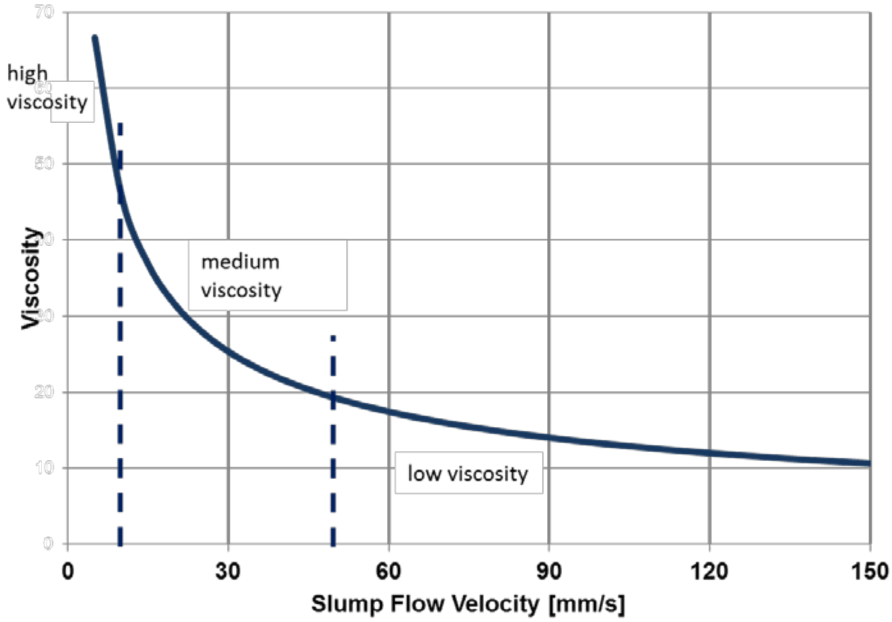
The fundamental properties characterising concrete workability are yield stress and viscosity. As there are currently no practical field tests to measure these properties directly, indirect measurements are required. Both the slump flow and slump flow velocity tests described in *Appendix A1* can be used to give an indirect measurement of the relevant characteristics. Figure 12 illustrates the correlation between yield and slump flow. Figure 13 shows the approximate correlation between viscosity and slump flow velocity.

Figure 12: Slump Flow Curve related to yield (qualitatively) and recommended range for tremie concrete (test in accordance with EN 12350-8 and ASTM C1611, see Appendix A1). Refer also to Figure 6.



Note: In this Guide, the slump flow is presented as the preferred parameter to represent yield stress A fuller explanation is contained in (Kraenkel, 2018) and briefly shown and discussed in Section 5.2.

Figure 13: Slump Flow Velocity Curve related to viscosity (qualitatively) and recommended range for tremie concrete (test in accordance with EN 12350-8 and ASTM C1611, see Appendix A1)



5.2 Test Methods to Characterise Fresh Concrete

Edition 1 of this Guide, in Appendix 1, described available tests to characterise fresh concrete with regard to rheology, workability, workability retention and stability.

As part of the R & D program, the tests described in Edition 1 were carried out on laboratory and field samples in order to determine the relevance and usefulness of each test, related to tremie concrete. A detailed review by the Technical University of Munich and Missouri University of Science and Technology determined that the important rheological parameters of yield stress and viscosity could both be adequately measured in the field by the slump flow and slow flow velocity, both evaluated by one test. In addition, this test allows the VSI to be determined.

The slump test and the flow table test are standard tests to determine workability in accordance with EN 12350-2 and -5. Based on the R & D work that has been carried out, the slump flow test gives a better correlation to the yield stress for tremie concrete than the slump test and flow table test. However, based on laboratory and site test data, approximate equivalents can be established.

For the range of slump flow 400-550 mm the equivalent range of slump was found to be 220-270 mm.

Note 1: Given the specified tolerance of 30 mm for the slump test, it is not considered appropriate for use with highly flowable tremie concrete.

For the range of slump flow 400-550 mm the equivalent range of spread from the flow table test was found to be 560-640 mm.

Note 1: Compared with the slump flow test the flow table test has a lower selectivity, and also uses dynamic impacts which may reflect better dynamic conditions (e.g. for concrete being vibrated).

Note 2: The initial spread (before the 15 hits) was found to be in the range 380-500 mm. These values are lower and less selective than those from the slump flow test as the energy supply is less with the lower cone (200 mm for the flow table and 300 mm for the slump flow test)

5.3 Suitability, Conformity and Acceptance Testing

The purpose of the suitability testing is to find a concrete mix which balances the sometimes conflicting requirements for the properties of fresh and hardened concrete i.e. workability, stability, workability retention and/or thixotropy, rate of strength gain and durability. To ensure that the required concrete performance during production is achieved it is recommended that the fresh properties listed in *Table 5.1* should be confirmed during suitability trials. It is important to recognise that successful performance of a tremie concrete is determined by a suite of tests and no single test will adequately describe all the required characteristics.

Conformity testing is an integral part of the production control of the supplier. The evaluation of conformity is the systematic examination to which the fresh concrete fulfils the specified requirements.

During execution of the deep foundations, the on-site acceptance testing proves the suitability of each load delivered. The acceptance testing should be carried out using slump flow and Visual Stability Index on every load, including the slump flow velocity at least once per week. Other tests recommended to demonstrate conformity, e.g. in stability, may be used on demand, in case of any doubt.

Depending on the nature of the work a higher rate of testing may be initially specified, reducing in frequency as confidence in conformance increases. Recommended tests and acceptance criteria for both suitability trials and ongoing conformity/acceptance testing are summarised in *Table 5.1.* Test details are provided in *Appendix A.*

Table 5.1: Recommended tests and values for suitability testing of tremie concrete at design stage

TEST		**determining**			**RELEVANCE for**	**Recommended RANGE for**
No		**Workability**	**Thixotropy**	**Stability**	**SUITABILITY**	**TARGET VALUES**
A1.1	Slump Flow	✔	✔*	−	M	400 – 550 mm
A1.2	Slump Flow Velocity	✔	-	−	R	10 – 50 mm/s
A1.3	VSI	−	−	✔	M	0
A2	Slump	✔	✔*	−	O	220 – 270 mm
A3	Flow Table	✔	✔*	−	O	560 – 640 mm
A4	Modified Cone Outflow	✔	-	−	O	3 – 6 s
A5	Manual Vane Shear	✔	✔*	−	O	See App A.5
A6	Workability Retention	✔	-	-	R/M**	≥ 400mm
A7	Static Segregation	-	-	✔	O/R**	≤ 10%
A8	Sieve Segregation	-	-	✔	O/R**	≤ 10%
A9	Bleeding	-	-	✔	O/R**	≤0.1ml/min
A10	Bauer Filtration	-	-	✔	O/R**	≤ 22 ml***

M = Mandatory; R = Recommended; O = Optional

** Note: information on thixotropy can be gained if the relevant test is executed after a resting time of the concrete as indicated in Appendix A.6.*

*** Note: for large pours over 200 m³ [260 cy].*

**** Note: The requirement on the concrete's filtration loss may be adjusted to the specific conditions in place, and the relevance of the deep foundation element, as described in Appendix A.10.*

Table 5.2: Recommended tests, tolerances and frequency for conformity and acceptance testing for tremie concrete prior and during execution of deep foundation works

TEST		RELEVANCE for	Recommended Target Value	RELEVANCE for	Recommended acceptance testing
No		CONFORMITY	TOLERANCE	ACCEPTANCE	FREQUENCY
A1.1	Slump Flow	M	± 50 mm	M	Each load
A1.2	Slump Flow Velocity	R	± 5 mm/s	O	1/week
A1.3	VSI	M	-	M	Each load
A2	Slump	O	± 30 mm	O	(Each load)
A3	Flow Table	O	± 30 mm	O	(Each load)
A4	Modified Cone Outflow	O	± 1 s	O	On demand
A5	Manual Vane Shear	O	N/A	O	On demand
A6	Workability Retention	R/M*	- 50mm	O	On demand/At start*
A7	Static Segregation	O/R*	+ 2%	O	On demand
A8	Sieve Segregation	O/R*	+ 2%	O	On demand/At start*
A9	Bleeding	O/R*	+ 0.02 ml/min	O	On demand/At start*
A10	Bauer Filtration	O/R*	+ 5 ml	O	On demand/At start*

M = Mandatory; R = Recommended; O = Optional

Testing frequency may be reviewed once target values have been reliably and consistently achieved.

** Note: for large pours over 200 m³ [260 cy].*

The recommendations in Table 5.1 and 5.2 are intended to be applied for deep foundations with depth > 15 m and high quality requirements (e.g. structural elements for permanent use). In more challenging situations, it may be appropriate to amend the acceptance criteria (e.g. reduce the acceptable filtration loss). In less onerous cases (e.g. shallow and/or unreinforced elements), it may be appropriate to reduce the frequency of testing and/or the requirements.

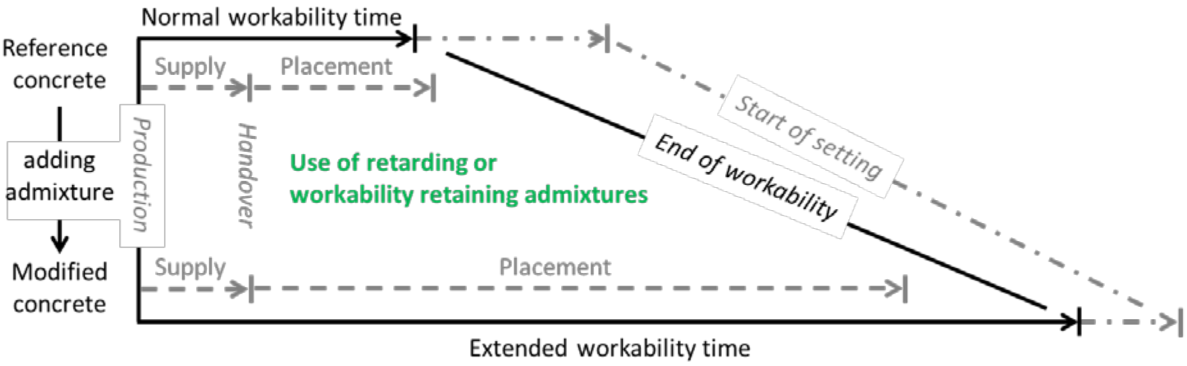
5.4 Control of Workability Retention

It is important that the Specifier (See Figure 2) makes a realistic assessment of the period over which certain properties should be obtained, or the decrease of workability should be limited, especially for large pours (e.g. greater than 200 m^3 [260 cy]), where supply capacity is limited, or where supply is complex due to a congested site. This assessment should include consideration of the following:-

- Period required to pour the pile/panel
- Transport distance/time from plant to site
- Concrete plant capacity
- Availability of approved back-up facilities
- Truck capacity and number of trucks
- Quality of site access
- Climatic conditions, in particular temperature
- Actual loss of workability over time, see *Annexes A and B*

A detailed consideration of the above factors will often result in the requirement to extend the workability retention (or flow/slump retention, sometimes also referred to as workability life or open life) using retarding or workability retaining admixtures, as illustrated in *Figure 14.*

Figure 14: Extension of workability time



The recommended workability retention can be specified as a minimum required workability at the end of the entire concrete placement. For foundation elements up to 60 m [200 ft] depth, a minimum slump flow of 400 mm [16 in] is recommended for the concrete at the end of the required workability time. For pours of deeper elements, the above minimum workability may not be required at the end of the entire pour depending on placement and tremie removal rate.

Note: Detailed recommendations for such extreme conditions cannot be made at this time but should be addressed in future editions of this guide, once extended numerical studies provide sufficient evidence for recommendations.

It should be noted that standards are currently being updated to give consistent guidance on sampling of fresh concrete and assessment of workability retention. Current draft guidance is provided in *Appendix A*.

5.5 Quality Control on the Concrete Manufacturing Process

Suppliers of ready-mixed concrete should work in accordance with the specified contract requirements (in Europe, EN 206 and its related National Annex). This guide provides additional aspects to be considered and which may influence the final agreed contract specification. The ready-mixed concrete producer should have product conformity certification with the following minimum requirements, wherever possible, though there are remote areas where it may be difficult to find suppliers with product conformity certification:-

- An approved quality management system e.g. EN ISO 9001
- Product testing by or calibrated against a laboratory accredited for the tests undertaken
- Surveillance that includes checking the validity of the producer’s declarations of conformity, by a certification accreditation body

  Note 1: Conformity control shall be in accordance with the conformity control requirements for designed concretes specified e.g. EN 206.

  Note 2: Provisions for assessment, surveillance and certification of production control by an accredited body should be as specified in relevant standards e.g. EN 206.

The manufacturing process plays a key role in the consistency of the batched concrete and is therefore most important for the performance of tremie concrete. It is good practice to be familiar with the supplier’s design, manufacturing and quality control process, prior to ordering concrete. The producer should inform the specifier of the status of the concrete production plant at the time of tender and immediately if any change in status occurs during the period between the time of tender and completion of supply.

In regions where suppliers of ready-mixed concrete with the required level of product conformity certification are not available, it may be possible to use a supplier with a lower level of quality assurance. It may then be the responsibility of the customer to ensure the correct quality and consistency (i.e. uniformity) of concrete supplied. As a minimum, suitably experienced personnel should check (or assess) the following items:-

- Calibration of weighting sensors to ensure correct mix proportions.
- The assumed free moisture content of the coarse aggregate.
  Note: Tremie concrete often contains a higher proportion of small aggregate than normal concretes and consequently the assumed free water content may be too low (Harrison, 2017)
- Calibration of flow meters where used for the addition of water etc.
  Note: Torque meters may be considered reliable for the intermediate ranges of workability.
- Method of measurement of admixtures, for example as specified in EN 1008.
- Calibration of moisture probes both, automatic where used to measure moisture contents in the fine aggregate, and hand held devices used to measure moisture content in the stock piles.

The following are considered good practice in order to supply tremie concrete with consistently suitable quality. Relevant requirements should be included in project specifications and include records for demonstration of conformity:-

- Moisture content of aggregates should be measured on a regular basis dependent on the volume of material being used, the weather conditions, the storage conditions, the sensitivity of the mix etc. It should be noted that the moisture content of fine aggregate will vary more widely than that of coarse aggregate. It is common practice to adjust moisture content based on daily observation of coarse aggregate. Moisture content of fine aggregate will vary more widely and as a minimum should be checked twice a day. However, modern batching plants normally have probes measuring moisture content of fine aggregate at the point of discharge to the mixer (in-flight) and will adjust water demand accordingly. For major projects in-flight moisture probes should be specified.

  Note 1: Monitoring of moisture content in the surface material of an aggregate bin that has not been recently disturbed may not be representative of the majority of the material in the bin.

  Note 2: Surface moisture contents and absorption values for fine and coarse aggregates should be validated regularly by oven drying of representative samples.

- Control of the actual water content in fresh concrete should be made on a regular basis.

  Note: Concrete is frequently batched using automatic controls that balance the volume of constituent added and the torque of the mixer. For tremie concretes with high workability, these measurements may not be accurate enough and measurement of actual water content is preferred.

- Mixing water including any re-cycled water should be checked weekly for its fines content and chemical composition in order to ensure compliance with relevant standards e.g. US standard ASTM C1602 (2012).
  Note 1: The use of re-cycled water may cause adverse effects on workability and therefore require additional admixtures to ensure the required workability is achieved. Workability retention should be retested if using recycled water.

Note 2: Some contractors are reluctant to accept recycled water due to their experiences with greater scattering of fresh concrete properties, probably due to varying fines contents and/or varying remains from super-plasticisers.

- Fine and coarse aggregate gradation of representative samples should be checked weekly or every time the supply source is changed.
- The mixer should be thoroughly cleaned at least once a day.
- Electronic copies of weigh batch records should be printed directly on each batch ticket or provided by the supplier within 24 hours of batching. This applies to producers who do not provide product conformity certification for the specified concrete.

  Note: All information needed by the user is on the delivery note and as there is a requirement for product conformity certification, the certification body as part of their routine practice will spot check that the batch records align with the specification (see Concrete Society Technical Report 76 on interpreting batch records. This is a complex procedure best left to the experts of the certification body).

- The concrete truck mixers should be emptied of any residual concrete or water before being filled.

  Note: The ready-mix concrete supplier should be required to declare for approval any waste minimisation system that involves the retention and re-use of returned concrete or its constituents.

6 Execution

6.1 General

This Section reviews techniques and methods used for concrete placement by the tremie technique in deep foundations (bored piles, diaphragm walls and barrettes).

European, American and International Standards and Codes of Practice vary. The Guide therefore makes recommendations as to what is considered good practice.

This Section does not cover “dry” pouring conditions where the concrete is usually allowed to free-fall over a certain height. European standard EN 1536 and ICE SPERW allow concreting in dry conditions if a check immediately before the placement proves that no water is standing at the base of the pile bore. The U.S. Department of Transportation FHWA GEC10, 2010 defines “dry as less than 75 mm [3 in] of water on the base of the bore, and an inflow not greater than 25 mm [1 in] in 5 minutes. In the case of greater inflow of water, it is recommended that the excavation is filled with water from an external source to overcome the inflow with positive fluid head within the excavation, and then to use the tremie technique for concrete placement. The placement of concrete (even with a tremie) into an excavation with excessive inflow of water entails a risk of the incoming water mixing with the fresh concrete.

6.2 Prior to Concreting

It is essential that the base of the excavation is reasonably free of loose debris, which can be stirred up by the initial charge of concrete from the tremie and may accumulate in the interface layer. It is difficult to remove all debris from the base. Minor amounts of debris are normally acceptable.

Where there is a high reliance on base cleanliness, such as load bearing elements that rely heavily on end bearing capacity, it is important that debris at the pile or panel base is kept to a minimum. The benefits of additional time taken to clean the base should be balanced against any negative effects that this could cause (e.g increased build-up of filter cake).

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 are available and some examples are provided in FHWA GEC10, and in ICE SPERW. Base grouting or extending the excavation depth may be considered to overcome base cleanliness issues.

It should be noted that the geometry of the excavation tool will dictate the shape of the base. With grabs and cutters, a curved profile is formed at the base. In such cases it is essential that the location of any base cleanliness checks are carefully considered and recorded. *Figure 15* shows the special situation of cutting into hard material using a trench cutter, where the base can only replicate the shape of the cutting wheels, including the over-cut zone in large panels with centre bites.

Bases of piles are cleaned using a cleaning bucket, submersible pump, air lift, or other proven system. Bases of diaphragm walls are normally cleaned using the excavation equipment or other proven system.

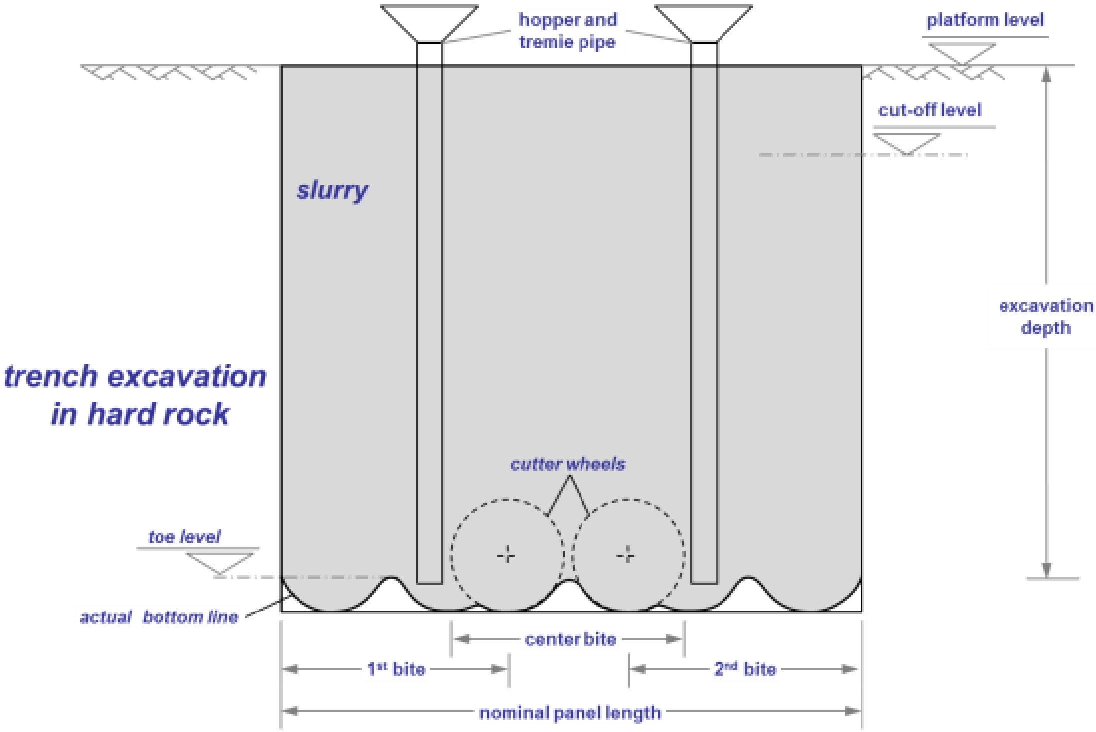
The best way to control the filter cake thickness is by controlling the support fluid properties. This is discussed in the EFFC/DFI Support Fluid Guide.

The support fluid should comply with the specified properties given in the EFFC/DFI Support Fluid Guide prior to insertion of the reinforcement cage and pouring of the concrete.

Before the insertion of the reinforcement cage (and commencement of pouring), it should be confirmed that the actual conditions are in accordance with the design and specifications e.g. excavation depth, nominal concrete cover (spacers) and reinforcement cage.

In multi bite diaphragm wall panels, the bottom level of each bite should be the same to within 0.5 m [2 ft] except in particular cases such as multi bite panels founded on inclined hard rock. Where the panel is stepped, the placement process must take this into account.

Figure 15: Base profile reflecting the excavation tool geometry (example shown using a cutter)



The time elapsing between the final cleaning of the excavation and commencement of concreting should be kept as short as possible. Where elements such as stop-ends or reinforcement cages are to be inserted, cleaning should be carried out before insertion. The cleaning procedure, as well as the time between operations, should be established on the first panels. If delays occur, the support fluid quality should be rechecked and additional cleaning carried out if necessary.

Debris and particles which settle out of the support fluid will normally be carried on top of the rising concrete surface in the interface layer which is discussed in more detail in the EFFC/DFI Support Fluid Guide. The concrete is over-poured above the theoretical level to allow for later removal of the unsound concrete above cut-off level, resulting in sound concrete at cut-off level.

6.3 Tremie Equipment

Gravity tremie pipes should have a minimum internal diameter of 150 mm [6 in], or six times the maximum aggregate size, whichever is greater (EN 1536). A diameter of 250 mm [10 in] is commonly used. Pressurised tremie systems (pump lines) may be smaller than 150 mm [6 in].

Tremie pipes should be made from steel, as aluminium reacts with concrete.

Segmental pipes should be connected by a fully watertight structural connection. Typical sections have a length of 1 m to 5 m [3 ft to 15 ft]. Longer sections are generally preferred as this leads to fewer joints, but the order of the various lengths has to be considered according to the specific conditions (e.g. depth of excavation, hopper elevation, embedment at first pipe removal, and for the last loads at low hydrostatic pressure). In general, the pipes should be split at every joint each time they are used, and stored vertically in a tremie frame, also to allow proper cleaning. There have been examples of joints failing during tremie handling, so full visual checking is strongly recommended.

- Solid tremie pipes (without joints) may be used on shallow excavations where handling of the tremie permits.
- The hopper should have as large a volume as possible. The filling rate must allow for a continuous concrete supply to the tremie during the initial embedment of the tremie pipe.
- The pipes should be smooth clean and straight so that the frictional resistance to the concrete flow is minimised.

6.4 Tremie Spacing

Piles are normally circular and a single tremie pipe placed centrally within the bore is usually sufficient. For diaphragm walls, codes specify various limits to the horizontal flow distance from 1.8 m to 2.5 m, [6 ft to 8 ft] with a maximum of 3 m [10 ft] (ICE SPERW, EN 1538, Z17). It is recommended that the distance is limited to 2 m [7 ft]. Longer travel distances of up to 3 m [10 ft] might be acceptable if the workability of the concrete is proven sufficient, in combination with clear spacing of reinforcement bars and concrete cover in excess of the minimum values. Full scale trials or numerical simulations (in particular by comparative studies) may assist in finding allowable values, see *sections 7 and 9*.

The tremie pipes should be positioned as symmetrically as possible in plan to avoid uneven rises in concrete level e.g central for a single tremie pipe and approximately 1/4 of panel length from each end with 2 tremie pipes.

6.5 Initial Concrete Placement

Initiation of the concrete placement is one of the most critical steps in the entire placement process as the first load of concrete has to be separated from the (supporting) fluid.

Both wet and dry initial concrete placement methods are described in various standards, guidelines and published technical papers (e.g. FHWA GEC10).

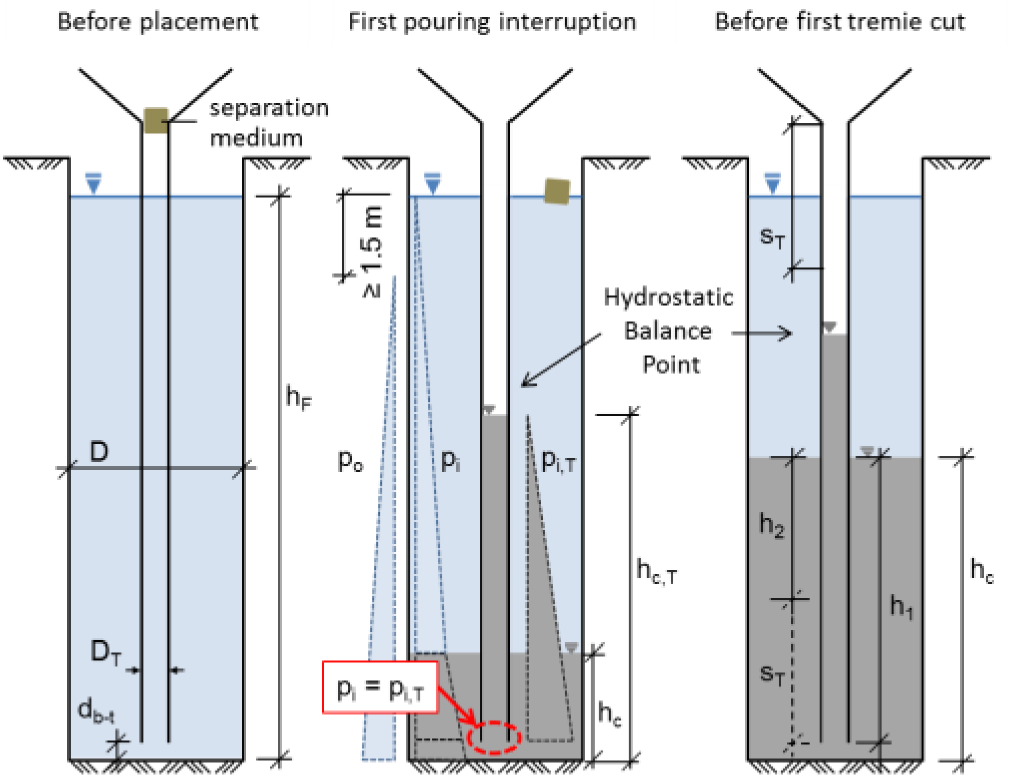
In the dry initial placement (often mistaken with “dry pour”) method, the concrete only gets into contact with the support fluid once it flows out of the tremie pipe. A steel or plywood plate with a sealing ring is placed on the bottom of the tremie pipe which enables fluid to be kept out of the pipe during lowering to the base of the excavation. The concrete is then discharged directly into the dry tremie pipe, and the pipe lifted by 0.1 m to 0.2 m [4 to 8 in] to allow the concrete to flow into the excavation. For deeper pours, it can be difficult to prevent fluid entering the tremie pipe through the segmental joints and/or prevent the tremie pipe from floating.

With the wet initial placement method, a separation medium must be used as the tremie pipe is full of fluid. Examples for such “plugs” include vermiculite granules (possibly bundled in a sack), inflatable rubber balls, sponges and foam balls. A steel plate is sometimes additionally used at the base of the hopper where the hopper is filled and the plate then lifted using a crane. The plug must prevent the initial charge of concrete from mixing with the fluid which would lead to segregation in the tremie. To start concreting, the tremie pipe should be lowered to the bottom of the excavation and then raised a short distance (no greater than the diameter of the tremie pipe) to initiate concrete flow and allow the plug to exit from the base of the tremie. ICE SPERW states that a sliding plug of vermiculate should have a length of 2 times the tremie diameter and that the tremie should not be lifted more than 0.2 m [8 in] from the base. For practical reasons the wet initial placement method is the preferred method.

Figure 16 shows the pressure conditions before and during the stages of the pour and highlights that before the first cut the tremie pipe must be sufficiently embedded. However, due to dynamic aspects of concrete flow, the actual concrete level in the tremie pipe, in particular at the interruption after the initial pour, might be lower than the hydrostatic balance point as indicated in *Figure 16*.

The required concrete level should be assessed for each specific site condition but in most circumstances a minimum of 5 m [15 ft] (6 m [18 ft] according to EN 1536) is required before the first split of the tremie. It is essential that a sufficient volume of concrete, which is defined as the quantity to fill the minimum height, is available on site before the pour is commenced.

Figure 16: Phases in the tremie pour sequence



Where:

h_F	Fluid level in excavation
D_T	Diameter of tremie pipe
D	Dimension (diameter or thickness) of excavation
$d_{b\text{-}t}$	Distance from bottom of excavation to tremie pipe outlet
h_c	Concrete level in excavation
$h_{c,T}$	Concrete level in tremie pipe (= hydrostatic balance point)
h_1/h_2	Embedment of tremie pipe before (1) / after (2) tremie pipe cut
s_T	Section length of tremie pipe section to cut, with: $h_2 \geq 3$ m [10 ft]
p_o/p_i	Hydrostatic pressure outside (o) / inside (i) of excavation
$p_{i,T}$	Hydrostatic pressure inside the tremie pipe

6.6 Tremie Embedment

The tremie requires a minimum embedment into the concrete that has already been poured. European execution standards (EN 1536, EN 1538) specify a minimum embedment of 1.5 m to 3 m [5 ft to 10 ft], with higher values for larger excavations. In general a minimum embedment of 3m is well accepted in practice.

If temporary casing is being used during the tremie concrete pour, the removal of temporary casing sections should be considered with respect to maintaining minimum tremie embedment. Removal of temporary casing sections will cause the concrete level to drop as concrete fills the annulus left by the casing. Prior to removing a section of temporary casing, the tremie embedment depth should be adequate to maintain the minimum required embedment as the concrete level drops during casing removal.

When two or more tremie pipes are used (see section 6.4) the tremie bases have to be kept at the same level (except where the base is stepped which requires special initial measures).

To get the concrete to flow, the weight of the concrete within the tremie pipe must overcome:-

- The resistance outside the base of the tremie pipe (hydrostatic fluid pressure)
- The resistance of the concrete already poured
- The friction between the concrete and the inside face of the tremie pipe

Some authors refer to the 'hydrostatic balance point' where the gravity force within the tremie is in equilibrium with the resistance to flow (*see Figure 16*). Any concrete added above the hydrostatic balance point will cause the concrete to flow, and the higher the pouring rate the faster the flow out of the tremie outlet.

There are strong technical arguments to avoid excessive tremie embedment. Greater embedment leads to lower head pressure, loss of energy supply and slower concrete flow. Embedments ranging from 3 m [10 ft] minimum to 8 m [25 ft] maximum are recommended. At the end of the pour, i.e. close to the platform level, it is acceptable to reduce the minimum tremie embedment to 2 m [7 ft].

For small diameter bored piles the maximum embedment may need to be increased to avoid the need to split the tremie before an individual truck load is fully discharged but suitability should be proven e.g. by full scale trials in case of critical conditions such as high viscosity (resistance to flow).

It is mandatory to measure the depth to the concrete at tremie positions after each load of concrete has been placed, which is often performed using a weighted tape. Where two or more tremie pipes are used in one panel it is essential to keep concrete levels outside the tremie pipes equal (within 0.5 m [2 ft]).

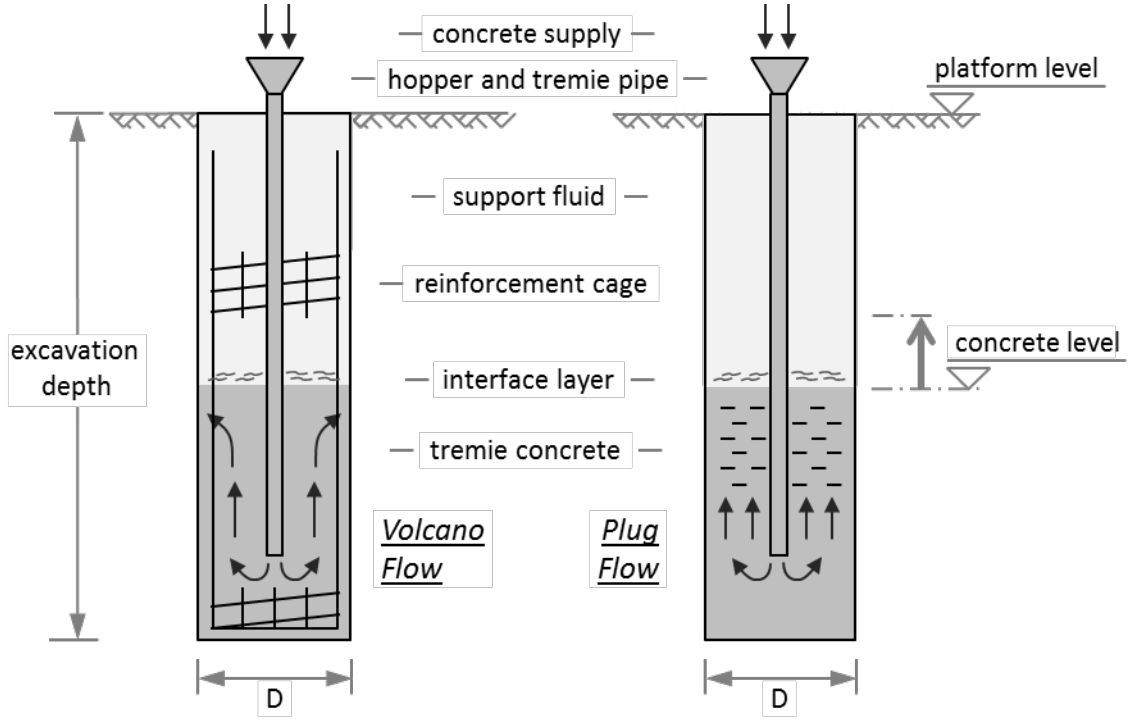
Concrete should flow freely from the tremie without the need of surging (rapid raising and lowering of the tremie). The need to surge the tremie in order to maintain flow is an indication of loss of workability. This can affect the concrete flow pattern and may risk mixing of support fluid and contaminated material on top of the concrete leading to debris entrapment. With proper mix composition and minimizing embedment, tremie surging should not be necessary.

A suitable methodology for re-embedding the tremie pipe after accidental removal above the level of the concrete, or in the case of interruption of concrete delivery, should be detailed in the submittals and/or agreed upon in advance of the commencement of execution of works.

6.7 Concrete Flow Mechanisms

Results from field trials (Littlechild and Plumbridge, 1998, FHWA GEC10, and Boehle and Pulsfort, 2014), and numerical modelling simulations (see section 9) have confirmed that there are two basic types of flow: ‘volcano’ and ‘plug’. These are shown schematically in *Figure 17*.

Figure 17: Schematic of Volcano and Plug Flow



Based on a limited amount of field test data and numerical modelling simulations, volcano flow is believed to be the most common flow type in deep tremie pours. The fresh concrete, after leaving the tremie pipe outlet and turning upwards, is understood to establish a laminar flow for a distinctive distance in a confined centre area of the excavation, following the path of least resistance to flow (around the tremie pipe), and then to spread outwards at the top of the concrete. The older concrete is displaced upwards and sidewards and is then “consumed” within the outer circumference of the excavation, where relatively high resistance to flow prevails. Consequently, volcano flow is common especially in structural deep foundations where a reinforcement cage represents a major obstruction to vertical flow. A rough excavation face will also resist the concrete flow and contribute to volcano flow.

Plug flow exhibits a plug of concrete on top of the concrete column inside the excavation (or well inside the cage) and above the tremie pipe outlet, which is raised upwards by a fluid pressure induced underneath by “pumping” fresh tremie concrete which displaces the older concrete to the top. It is assumed that the fresh concrete is not mixing into the plug. An extreme case of plug flow would imply that the plug concrete is not sheared i.e. that it is internally at rest and prone to thixotropic effects. Plug flow is considered more probable in cases where a very low friction at the outside is prevalent (e.g. no cage and a smooth excavation surface) or for the inner section of a wide excavation, the latter which would result in combined volcano and plug flow.

There are multiple interdependent factors determining which type (or combination of types) of flow actually occurs. The flow in an individual deep foundation element can also vary during a single pour e.g. due to time dependent rheology of the concrete, local steel congestions or changes in the effective hydrostatic conditions. To better understand these complex interactions and isolate the most sensitive parameters the numerical modelling, discussed in Section 9, can be used.

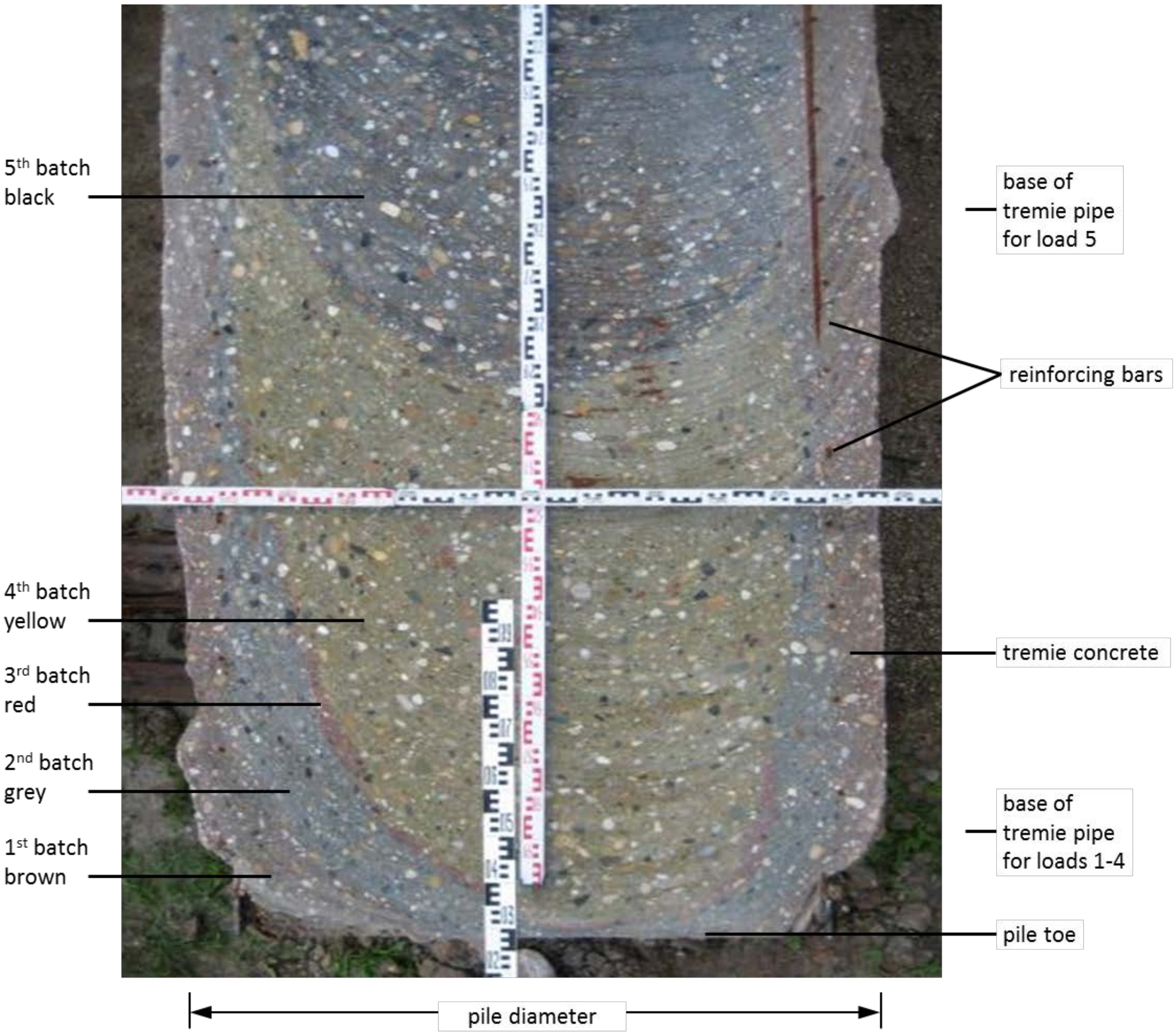
Concrete flow patterns have occasionally been investigated in the field but are still not fully understood. Further research is on-going, where the concrete flow patterns from the tremie pipe are numerically modelled, including the interface layer, using fluid dynamics programs or simulations (Böhle and Pulsfort, 2014).

Figure 18 shows a cut longitudinal cross section of a bored pile which had been cast using dyed concrete in order to investigate the flow pattern under specific conditions. The visible flow pattern shows earlier poured concrete at the outside (especially in the cover zone) and later poured concrete in the centre. The yellow and black dyed concrete batches were poured from two different outflow levels before and after splitting the tremie pipe.

The associated flow mechanism is understood to be systematic for a multi-stage pouring process where the tremie pipe is lifted in defined steps and displaces older concrete to the top and to the sides, indicative of the volcano flow mechanism.

Note: the red dyed concrete from the 3rd batch is only visible as a thin layer between the 2nd (grey) and 4th (yellow) batch. This might indicate a change in the flow pattern, e.g. by a distinctive variation in rheology, or forced by the boundary conditions (within the excavation)

Figure 18: Cross section of a bored pile cast with differently dyed loads of tremie concrete (Böhle and Pulsfort, 2014), indicating volcano flow



The dominant rheological property affecting the concrete flow pattern is the yield stress (indicated by the slump flow). The viscosity (indicated by the slump flow velocity) can have an effect on the overall time required for a pour (slower flow of concrete) and may affect the demand for workability retention, which should be reduced wherever possible. The viscosity also directly effects the resistance to flow of the (horizontal) concrete through windows in the reinforcement cage.

Where yield stress and viscosity increase with time, it may be necessary to adapt execution techniques during the pour e.g reducing the tremie embedment depth towards the end of the pour.

6.8 Flow around Reinforcement and Box-Outs

As set out in *Section 2*, special consideration has to be given for any restriction to concrete flow. Any obstruction is a resistance to flow and will decrease the potential of the concrete used to properly flow around and embed a reinforcement bar or box-out. As the actual flow is a function of energy at the point of resistance, congestion is more critical at greater travel distances from the tremie pipe outlet and at higher elevations where the concrete head pressure is lower.

Detailing of the reinforcement cage, box-outs etc. has to comply with the codes (see *Appendix E)*. In addition, Numerical Modelling may be used to assess the sensitivity to changes in detailing and determine the least disruptive configurations.

Spacer blocks and other embedded items should be profiled to facilitate the flow of concrete.

6.9 Concreting Records

The depth of the concrete level at each tremie position and the embedded length of the tremie pipe recorded should be measured and recorded after the discharge of each load of concrete.

The depths measured, volumes placed, tremie lengths and casing lengths should be plotted immediately on a graph during the pouring operation and be compared with the theoretical values, considering the effects of excavation over-break. An example of such a graph is given in EN 1538 and in FHWA GEC10.

Such a comparison can help identify areas where over-break may have occurred or where concrete may be filling voids. Under-break is rare and under-consumption of concrete might indicate an issue such as instability, collapse, or mixing of support fluid, debris or soil with concrete. These measurements can identify an unusual condition in an excavation where more investigation may be warranted.

7 Full Scale Trials

An effective way to obtain information on any deep foundation element is to install one or more full-scale test elements. These should ideally be constructed using the same installation technique, 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 extent and scope of the trial works should be proportionate to the project size, complexity and risks. The components to be tested should be selected from a review of:-

- The design and detailing
- The fresh concrete performance
- The contractors overall experience and capability
- The experience in the given ground conditions

This may require excavation to expose constructed elements to a significant depth.

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 must be recognised by the client at an early stage, and specified in detail in the tender documents.

When budget and/or time schedule constraints do not allow for such full-scale trials, it is recommended to at least perform on-site concrete trial testing in addition to the design trials typically performed in the supplier’s laboratory.

8 Quality Control of Completed Works

8.1 General

It is essential that the contractor complies with relevant standards for quality assurance and control, and that the production process is supervised and undertaken by persons with appropriate qualifications.

Concrete placed in bored piles, diaphragm walls and barrettes is normally cast against the face of an open excavation and the placement process is not visible from the surface. Some imperfections of the hardened concrete of the deep foundation element are possible even though good practice construction methods were applied by the contractor. Quality control requirements for the completed works should therefore make allowance for acceptance of some imperfections where these are not significant with regard to the structural performance and durability of the completed works. To support efficient and consistent inspection and acceptance, acceptable imperfections should be clearly identified in work procedures and inspection and test requirements.

Identification of acceptable imperfections may be based on past experience or through construction trials undertaken prior to the commencement of the main works. It is normally far better to spend time and effort on trials before the works commence, rather than specifying detailed and expensive quality control tests after completion. Another option is to expose and test a limited sample of piles or wall panels after the construction of the first elements and this can form part of the QA/QC procedures allowing any required corrective action(s) to be implemented at an early stage.

8.2 Post-Construction Testing Methods

A number of methods, both intrusive and non-intrusive are commonly available to provide some information regarding the geometry and the quality of the pile or wall.

An overview of methods is given in *Appendix C*.

Non-intrusive test methods are often difficult to interpret correctly and this requires specialist knowledge and experience.

Imperfections can generally fall into one of three categories:-

- Anomalous material
- Channelling
- Mattressing (may also be referred to as ‘shadowing’ or ‘quilting’)

A further description of each category of imperfection, together with examples, is given in *Appendix D*.

If imperfections become defects and if these are frequent, it can be possible to postulate an imperfection formation mechanism, which if detected early enough will enable changes to materials or processes to avoid further occurrences.

Imperfections can be caused by concrete that does not have appropriate flow properties or the adequate stability for the detailing and placement procedure in place, or by poor workmanship. Applying the recommendations of this Guide, especially by following the mutual approach of interaction between all parties involved, should help to reduce the imperfections to an absolute minimum.

9 Numerical Modelling of Concrete Flow

9.1 Introduction

Numerical modelling methods (e.g. using a Bingham Fluid Model) are extremely useful to understand the importance of individual factors affecting the flow of the concrete as well as assessing the sensitivity to changes in each factor, as set out in *Table F.1*.

By setting rheological properties of the concrete and support fluid as well as defining the boundary conditions, it is possible to realistically model the bulk flow of the concrete inside an excavation.

9.2 Studies undertaken

The Task Group has worked with Academic Partners to determine fundamental interdependencies and corresponding sensitivities by reviewing model studies.

Figure 19 illustrates results from a 1.5 m diameter bored pile with a depth of 16 m and a reinforcement cage, with concrete pour simulating staged lifting of the tremie pipe. More simulations with numerical models from the Academic Partners are summarised in Li et al, 2018.

Simulations demonstrate that bulk flow can be modelled successfully and single factors can be isolated to show their individual impact on flow mechanisms e.g that pouring much lower yield stress concrete into already placed (high yield stress) concrete can lead to irregular flow patterns.

Figure 19: Simulations presenting volcano flow of bulk concrete by velocity streamlines (left), and by dyed concrete following a staged lifting of the tremie pipe (Li et al, 2018)

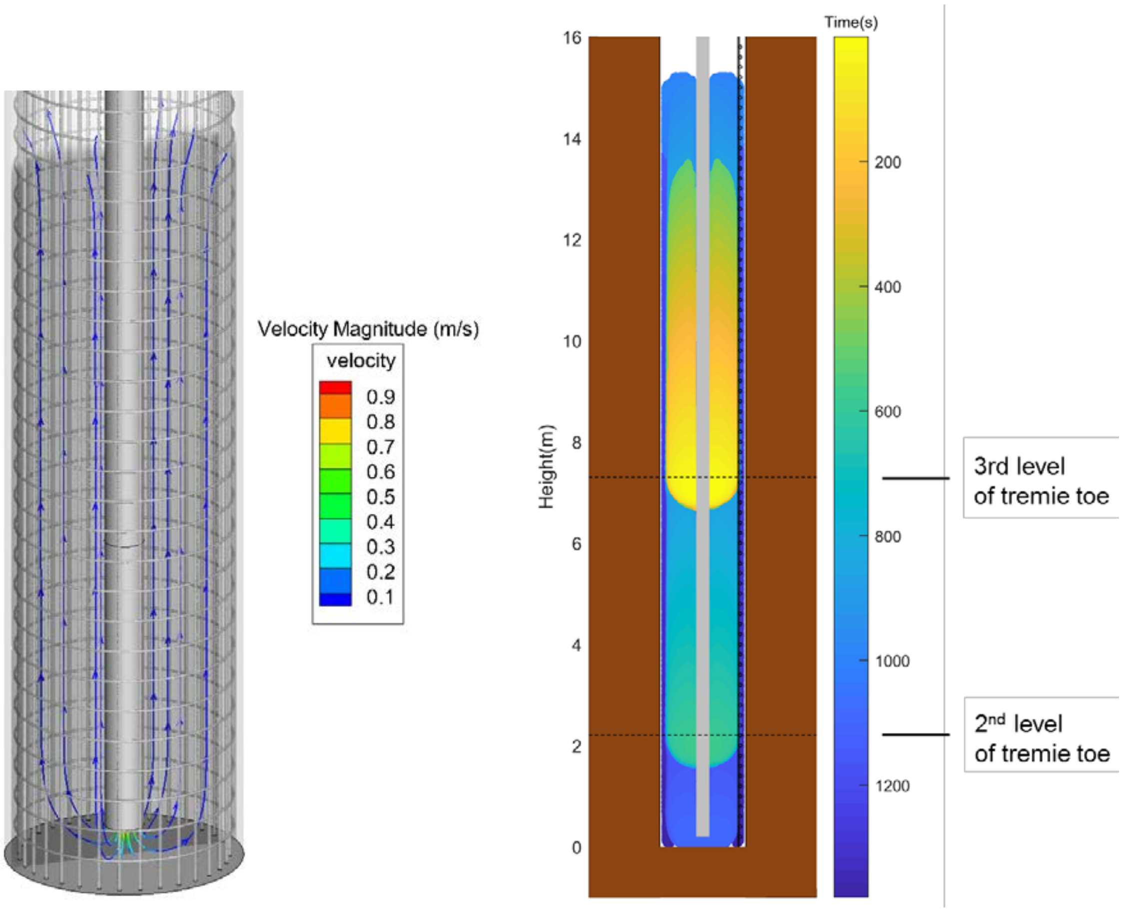
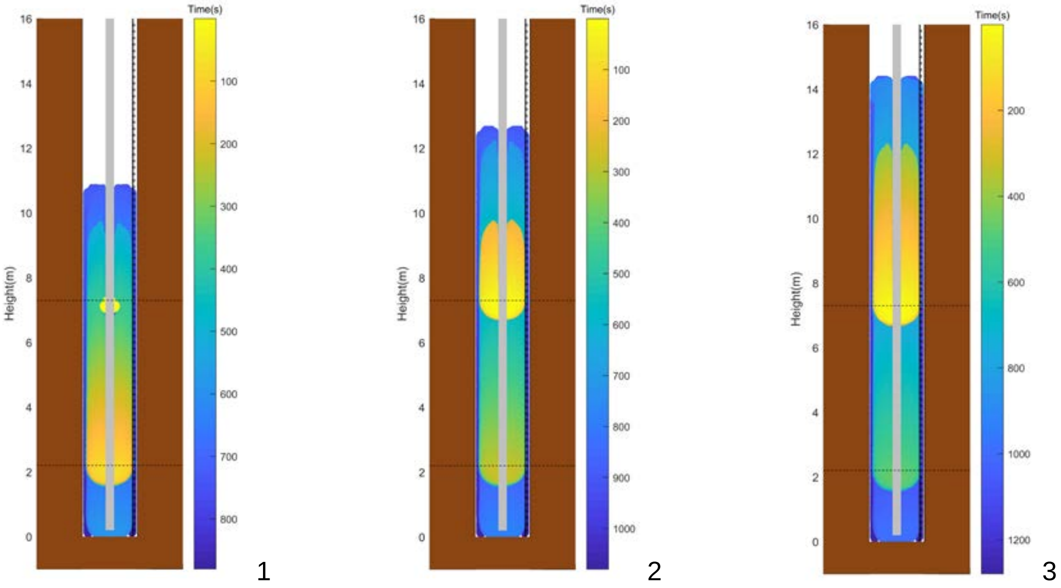


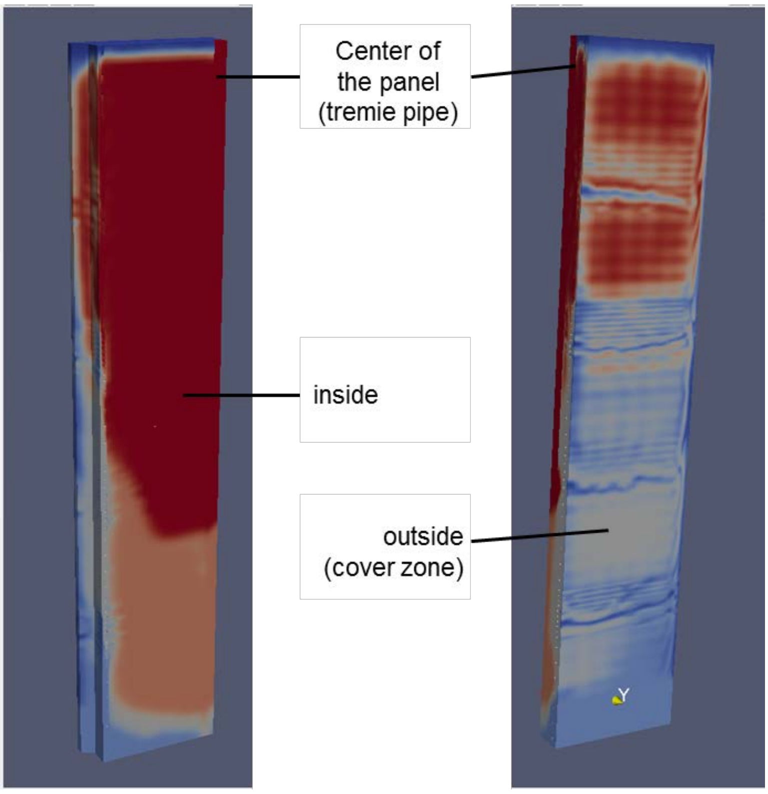
Figure 19 (cont.):



1 2 3

Figure 20 shows a simulation of a reinforced diaphragm wall panel with a variation in clear reinforcement spacing at different elevations, highlighting the risk for inclusions in the cover zone due to restrictions to flow (Li et al, 2018).

Figure 20: Simulations presenting volcano flow of bulk concrete in a quarter of a diaphragm wall panel, shown from the inside (to the left) and from the outside of a quarter panel (to the right), with inclusions due to restriction of concrete flow (images courtesy of Jan van Dalen)



A review of the model studies has resulted in a number of important conclusions and these are discussed in Table F.1. Further details on Numerical Modelling Methods are given in the joint research paper by the Task Group and the Academic Partners (Li et al, 2018).

9.3 Limitations

Processing time for simulations is dependent on the degree of detail of the model itself and can extend, with present computer technology, up to a number of weeks for each individual numerical model simulation. Accurately defining the physical shape and size of the reinforcement cage greatly increases computation time. The option to replace the cage with a porous membrane gives good correlation but involves far less computation time (Roussel and Gram, 2014).

It is important to balance the complexity of the model with the envisaged sensitivity to the effect of change in parameters (based on experience from earlier simulations) in order to reduce the computation time and thereby allow more simulations to be carried out.

Numerical simulation is a powerful tool to solve the governing partial differential equations derived from the physical model. Hence the significance of numerical simulation is limited to the capacity of the underlying physical model (e.g. the Bingham fluid model).

Further work is ongoing using full scale trials and then validating the findings from a model against the actual trial.

Appendix A – Test Methods to Characterise Fresh Concrete

The practical tests described in this Appendix can be used to determine:-

- Workability, represented by viscosity and yield stress
- Workability retention, including also thixotropy
- Stability

A1.1 Slump Flow Test in accordance with EN 12350-8 and ASTM C1611

Principle: The slump flow is a measure of the workability, and can be directly related to the yield stress.

Procedure: The fresh concrete is filled in a form that consists of a 300 mm [12 in] high hollow truncated cone, see *Figure A.1*. When the cone is raised the concrete will slump and flow. The final diameter of the concrete is measured (slump flow in mm).

Remarks: This test can be combined with the Slump Flow Velocity Test (A1.2) and the Visual Stability Index Test (A.1.3).

A1.2 Slump Flow Velocity Test

Principle: The slump flow velocity is a measure of the workability, and can be directly related to the viscosity.

Procedure: The fresh concrete is filled in a form that consists of a 300 mm [12 in] high hollow truncated cone, see *Figure A.1*. When the cone is raised the concrete will slump and flow, and the time t_{final} [s] taken for the concrete to spread to the final diameter D_{final} [mm] is measured. The travel distance (D_{final} - 200)/2 [mm] divided by the time taken t_{final} [s] is the slump flow velocity [mm/s].

Remarks: This test can be combined with the Slump Flow Test (A1.1) and the Visual Stability Index Test (A.1.3).

The original test specifies a T_{500} flow time as the time the concrete needs to spread to a diameter of 500 mm [20 in]. Since common tremie concrete may not necessarily spread that far, this specific measure test is deemed inapplicable for tremie concrete.

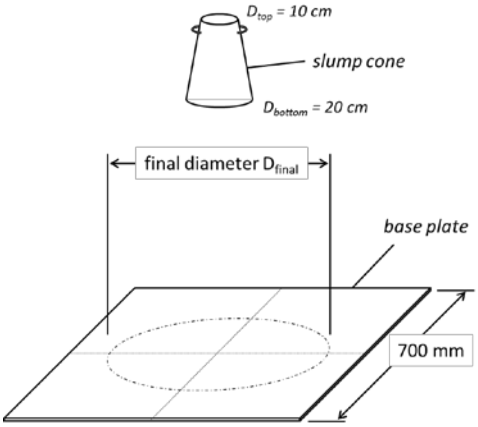


Figure A.1: Test equipment for combined slump flow, slump flow velocity and VSI test (A.1)

A.1.3 Visual Stability Index Test in accordance with ASTM C1611

Principle: The visual stability index (VSI) is the result of a visual assessment and classifies the segregation resistance.

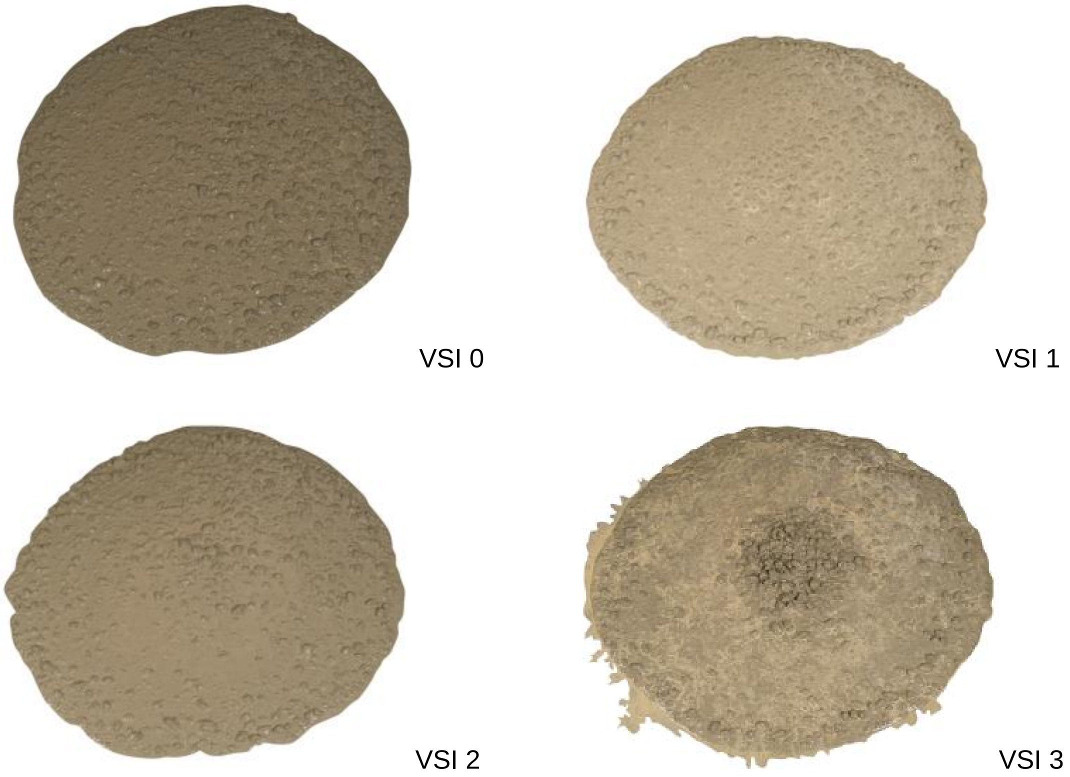
Procedure: Same as with slump flow, see *Figure A.1*, followed by visual inspection using the criteria listed in Table A.1.

Remarks: This test can only indicate high segregation tendency and may not be sufficient to detect sensitive mixes. In cases of doubt the static segregation test (A.7) or the sieve segregation test (A.8) should be used.

Table A.1: Visual Stability Index VSI classes (according to ASTM C1611)

VSI VALUE	CRITERIA
0 = Highly Stable	No evidence of segregation or bleeding
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass
2 = Unstable	A slight mortar halo ≤ 0.5 in [10 mm] and/or aggregate pile in the center of the concrete mass
3 = Highly Unstable	Clearly segregating by evidence of a large mortar halo > 0.5 in [10 mm] and/or a large aggregate pile in the centre of the concrete mass

Figure A.2: Examples of Visual Stability Index Classes



VSI 0

VSI 1

VSI 2

VSI 3

Photo courtesy of BASF Corporation

A.2 Slump Test in accordance with EN 12350-2, ASTM C143

Principle: The slump of the concrete gives a measure of the workability.

Procedure: The fresh concrete is filled and compacted in a mould that consists of a 30 cm [12 in] high hollow truncated cone, see figure A.1. When the cone is raised the concrete will slump and the vertical distance the concrete has slumped is measured.

Remarks: A serious lack of stability can potentially be detected visually.

A.3 Flow Table Test in accordance with EN 12350-5

Principle: The spread of the concrete gives a measure of the workability.

Procedure: The fresh concrete is filled and compacted in a mould which consists of a 20 cm [8 in] high hollow truncated cone. After raising the cone the plate is lifted and dropped 15 times which leads to the final spread which is measured.

Remarks: A serious lack of stability can potentially be detected visually. Due to the impacts from dropping it may be possible to detect a tendency for dynamic segregation.

A.4 Modified Cone Outflow Test

Principle: The outflow time of the concrete from the modified cone is a measure of the workability, and can be directly related to the viscosity.

Procedure: A hollow cylinder is mounted on top of an inverted, hollow truncated cone, with a flap at its bottom opening, which is closed before commencement of testing, see *Figure A.3*.

20 litres of fresh concrete is filled in the form with an excess above the top. The surface is struck off using a rod or scraping ruler. The filling operation should be performed within 1 min.

Within another 1 min, the flap is quickly opened and the out-flow time of the free-falling concrete is recorded until the cone is empty. Time is recorded to an accuracy of 0.1 s.

Remarks: The height of the cylinder is approx. 465 mm, with a constant inner diameter of 200 mm to contain 10 litres of fresh concrete together with the cone.

The inverted cone of the slump test (without the extra cylinder on top) can also be used. As the outflow time will be much shorter the result may be more reliable for concrete mixes of higher viscosity. If this test is envisaged to be used for conformity or acceptance testing, a target value should be determined and agreed within the suitability testing.

Figure A.3: Equipment (example) for the Modified Cone Outflow Test (A.4)

A.5 Manual Vane Shear Test

Principle: The shear resistance of a fresh concrete is a measure of its yield stress.

Procedure: Prepare a specimen of a fresh concrete sample in a bucket of sufficient volume and about 20 cm in height.

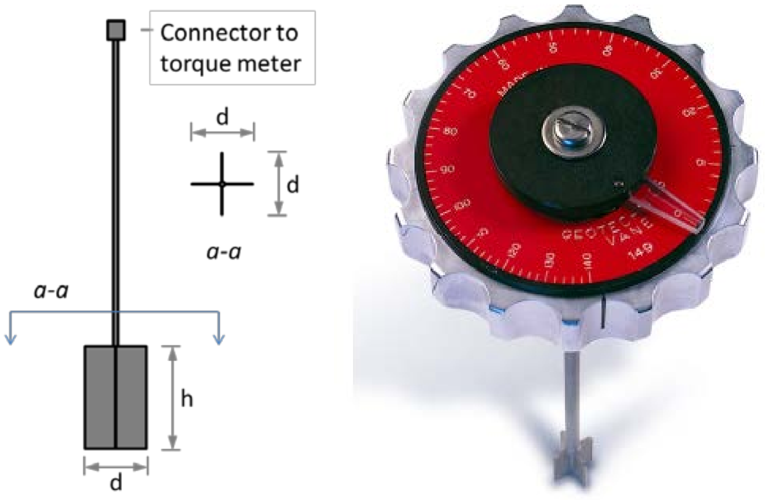
On the gauge of the torque meter, move the pointer counter-clockwise to zero.

Gently lower the shear vanes into the specimen to without disturbing the concrete sample. The top of the vanes should be at least 50 mm below the top of the concrete. Rotate the vane shear tester manually and read the maximum torque.

Remarks: A difference in torque measured in fresh concrete before and after resting is an indication of the concrete's thixotropy. Use up to 5 vane cells to test a series of concrete specimens at different resting times. Insert a cell in each specimen and test for its shear e.g. instantly and after 2, 4, 8 and 15 minutes. The increase of static yield stress is a direct measure for the concrete's thixotropy. A 100% increase in 15 minutes might be assessed as excessive thixotropy. For absolute assessment of allowable thixotropy a correlation to slump flow must be established.

In order to ensure sufficient selectivity the vanes shall be adapted, compared to typical vanes used for cohesive soils. The vane shear cell shall have a height of 100 mm and a diameter of 60 mm (4 blades at 90 degree angle each 30 mm wide), see *Figure A.4*. The axle shall be of sufficient length (about 300 mm) so that the vanes can be lowered well below the concrete surface.

Figure A.4: Axis and Vane Shear Cell dimensions for the Manual Vane Shear Test (New Zealand Geotechnical Society, 2001)



A.6 Workability Retention Test

Principle: The workability retention test measures the time span over which the concrete retains a specified slump flow.

Procedure: Repeat the slump flow tests (A1.1) at discrete intervals up to the assessed total pouring time needed for the specific element. EN 12350 (Testing Fresh Concrete) is currently being updated to introduce requirements for sampling and storage for workability retention testing. Draft requirements are included below.

Batch fresh concrete (for field trials preferably 3 m^3 [4 cy] but a minimum of 1m^3 [1.3 cy]).

Store the sample (or sufficient sub-samples) in sealable cylindrical containers made from non-absorbent material not readily attacked by cement paste, for receiving and storing increments of concrete. The ratio of height to diameter shall be in the range 0.7 to 1.3 and of sufficient size to fully retain the sample.

The quantity of the concrete sampled shall be not less than 1.5 times the quantity estimated for the tests and sufficient to fill the sealed container to within 25 mm to 50 mm of the cover.

Where the sample is intended to be used to measure slump retention at a specified time, the concrete from the sealed container should be emptied on the remixing container or tray and remixed using a shovel or scoop before carrying out the test.

Perform slump tests every 1 hour (2 hrs for life > 4 hrs)

Remarks: To check a concrete mix for thixotropic tendency, fill two slump cones with fresh concrete, and perform one slump flow test immediately. After a resting period of 15 minutes, perform the second slump flow test. If the difference in values is greater than 30 mm the test should be repeated.

Preliminary findings from the Research and Development Project indicate that thixotropy is significant in cases where the slump flow after 15 minutes of rest is 50 mm (or more) below the initial value

A.7 Static Segregation Test (or Washout Test) in accordance with ASTM C1610 and German DAfStb Guideline on SCC

Principle: The test evaluates static segregation by variation of coarse aggregate distribution over height.

Procedure: A hollow column of 3 connected cylinders is filled and compacted with fresh concrete, see Figure A.5 (the original standard and guideline allow no compaction or vibration, for SCC mixes). After a standard period, e.g. 2 hours, the proportion of coarse aggregate in the top and bottom cylinders is determined by washing and sieving. The difference in coarse aggregate is a measure of segregation.

Remarks: The test was developed for self-compacting concrete (SCC) with intentionally low yield stress, where segregation of aggregates is controlled by viscosity and is therefore time dependent. A longer standing time than the fifteen minutes period for SCC is deemed more appropriate, hence the standing times could be adapted depending on the workability time. Limited experience for this test exists for tremie concrete.

If the full setting time shall be taken into account the Hardened Visual Stability Index (HVSI) Test in accordance with AASHTO PP58-12 can be used. It also evaluates static segregation by examination of aggregate distribution, but in a hardened test specimen sawn in two, not needing specialist equipment other than a concrete saw.

Figure A.5: Arrangement for static segregation test in accordance with ASTM C1610

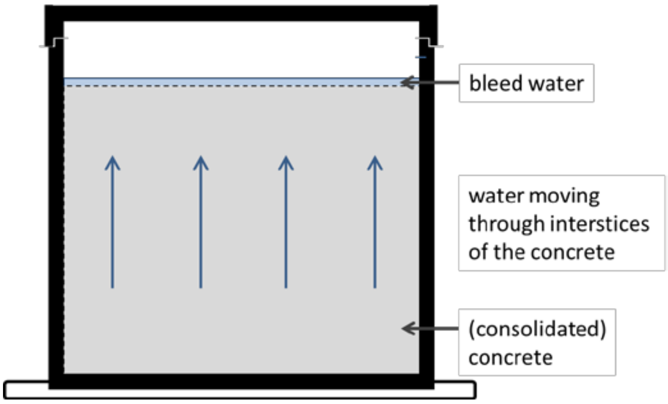
A.8 Sieve Segregation Test in accordance with EN 12350-11

Principle:	The amount of material passed through a sieve with 5 mm square openings in a container is a measure of segregation.
Procedure:	A sample of 10 litres (± 0.5 l) of fresh concrete is stored for 15 minutes, in a bucket with a lid to avoid evaporation. Weigh an empty container, put the (dry) sieve on top and weigh again, or set the balance to zero. After 15 minutes resting time take off the lid from the bucket and check for bleed water (record observation). Fill an amount of 4.8 kg (± 0.2 kg) of the concrete sample (including any bleed water) from a falling height of 500 mm (± 50 mm) continuously and carefully onto the sieve. After 120 s (± 5 s), remove the sieve vertically without vibration. The amount of material in the container is recorded as the segregated portion in % of the mass poured onto the sieve.
Remarks:	-

A.9 Bleeding Test in accordance with EN480-4 and ASTM C232

Principle:	The amount of water on the surface of concrete in a container is a measure of bleed, see figure A.9.
Procedure:	Concrete is inserted into a cylindrical container. The segregation of water at the surface is measured every 1 hour until the bleeding stops (as the concrete sets).
Remarks:	The time at start of bleeding and the constant bleed rate (see figure 8 in section 3.3) after commencement of bleeding are essential to describe the bleeding potential. An average bleeding rate after 2 hours of less than 0.1 ml/min is considered acceptable.

Figure A.6: Schematic set-up to determine bleed due to gravity



A.10 Bauer Filtration Test

Principle: The test simulates the water retention ability of fresh concrete under pressure and determines the filter loss through a filter, as shown in Figure A.6.

Procedure: A cylindrical container is filled with 1.5 litres [0.4 US gallons] of fresh concrete and pressurized with compressed air at 5 bar [73 psi] for 5 minutes. The water which separates from the bulk concrete through a filter paper is collected at the bottom of the container in a cylinder. The recorded filter loss is a measure of the filter stability of the concrete.

Remarks: The maximum aggregate size should be limited to 20 mm.

According to an acceptance criterion of 15 l/m^3, for tremie concrete in deep foundations (>15 m [50 ft] depth), the corresponding test value for the 1.5 l [0.4 US gallons] sample is approx. 22 ml [0.7 oz].

Industry internal tests indicate a correlation between the 'Austrian' concrete filter press test (Austrian Guidelines on Soft Concrete, Merkblatt, Weiche Betone, 2009) and the Bauer filtration test which is $V_{\text{loss-15,ÖVBB}}$ [l/m^3] / $V_{\text{loss,BAUER}}$ [l/m^3] = 1.8 (approx. 2).

The measured filter cake thickness is an additional measure for the concrete's robustness against loss of workability.

Note: The following "green light graph" may assist in determining the acceptable filtration loss measured with the BAUER filtration test. It may be reduced down to 12 ml in very challenging cases but can also be increased up to 32 ml or even 42 ml in less onerous cases.

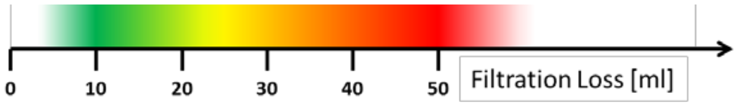
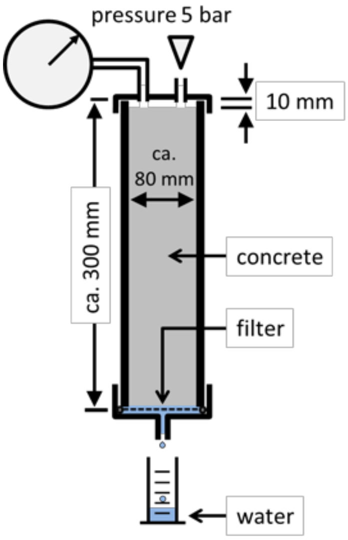


Figure A.7: Test arrangement to determine water loss from pressurized fresh concrete (Bauer).



Note: The test equipment is based upon the standard testing equipment for drilling fluids in accordance with API RP 13B-1, also referred to in EN ISO 10414-1.

Composition of Fresh Concrete

In order to verify that the actual composition complies with the design values, tests for density, water content, water/cement ratio, content of fines < 0.125mm [125 mesh] and content (or shape) of coarse aggregates may be carried out by a specialised laboratory.

The Oven Drying Test, where mix water is evaporated from the concrete by either low temperature oven or microwave, can be performed on site to determine the water content.

Appendix B – Concepts for Use of Additions

Specified minimum cement contents for concrete in deep foundations are often not necessary to obtain the required strength class, but to obtain specific fresh properties. Additions like fly ash and GGBS are often used to replace part of the cement, which in turns affects the fresh concrete's workability, flow retention and stability, as well as strength, durability and overall sustainability.

Three concepts are available for the use and application of (reactive) Type II additions (EN 206):-

1) The k-value concept,
2) The Equivalent Concrete Performance Concept (ECPC) and
3) The Equivalent Performance of Combinations Concept (EPCC).

The rules for the application of the three concepts vary within the different CEN member states. For each project, the concept should be carefully considered, both from a technical and an economical point of view.

K-Value Concept

The k-value concept is a prescriptive concept. It is based on the comparison of the durability performance of a reference concrete with another one in which part of the cement is replaced by an addition as a function of the water/cement ratio and the addition content.

The k-value concept permits type II additions to be taken into account:-

- By replacing the term "water/cement ratio" with "water/(cement + k * addition) ratio" and;
- The amount of (cement + k * addition) shall not be less than the minimum cement content required for the relevant exposure class.

The rules of application of the k-value concept for fly ash conforming to European standard EN 450-1, silica fume conforming to EN 13263-1, and ground granulated blast furnace slag conforming to EN 15167-1 together with cements of type CEM I and CEM II/A conforming to EN 197-1 are given in corresponding clauses in EN 206.

Modifications to the rules of the k-value concept may be applied where their suitability has been established (e.g. higher k-values, increased proportions of additions, use of other additions, combinations of additions and other cements).

For a further description of the full procedure and application of the k-value concept, the reader is referred to CEN/TR 16639 (2014).

Equivalent Concrete Performance Concept (ECPC)

The principles of the Equivalent Concrete Performance Concept have been introduced in EN 206.

This concept permits amendments to the requirements for minimum cement content and maximum water/cement ratio (w/c) when a combination of a specific addition and a specific cement source is used where the manufacturing source and characteristics of each are clearly defined. It shall be proven that the concrete has an equivalent performance especially with respect to its interaction with the environment and to its durability when compared with a reference concrete in accordance with the requirements for the relevant exposure class.

The reference cement shall fulfil the requirements of EN 197-1 and originates from a source that has been used in practice in the place of use within the last five years and used in the selected exposure class. The reference concrete shall conform to the provisions valid in the place of use for the selected exposure class.

The concrete composition and the constituent materials for designed and prescribed concrete shall be chosen to satisfy the requirements specified for fresh and hardened concrete, including consistence, density, strength, durability, and protection of embedded steel against corrosion, taking into account the production process and the intended method of execution of concrete works.

Equivalent Performance of Combinations Concept (EPCC)

The principles of the ”Equivalent Performance of Combinations Concept” permit a defined range of combinations of cement conforming to European standard EN 197-1 and addition (or additions) having established suitability that may count fully towards requirements for maximum water/cement ratio and minimum cement content which are specified for a concrete.

The elements of the methodology are:-

1) Identify a cement type that conforms to a European cement standard and that has the same or similar composition to the intended combination
2) Assess whether the concretes produced with the combination have similar strength and durability as concretes made with the identified cement type for the relevant exposure class
3) Apply production control that ensures these requirements for the concretes containing the combination are defined and implemented.

In Europe there are three methods applied to establish the equivalent performance of combinations - the UK method, the Irish method and the Portuguese method. These three methods have been developed separately and differ considerably in the requirements for the control of the combinations. The three methods are fully described in CEN/TR 16639 (2014).

Appendix C – Methods for Testing Completed Works

Testing of completed works is not mandatory for geotechnical works if their design complies with the relevant standards, and execution complies with both execution standards and industry good practice. Post-construction testing has however become more frequent recently. Generally, tests are used according to project specifications. Some tests need to be prepared before execution of the foundation, others can still be applied when there is reason to suspect a defect exists, see *Appendix D.*

Both destructive and non-destructive testing methods require expert knowledge for performance and interpretation. Technician-level expertise is required for conducting the tests while interpretation of results should be done by a qualified engineer, in consultation with the project geotechnical engineer.

In addition to the list of direct testing methods, cross-hole sonic logging (CSL) and thermal integrity profiling (TIP) are described representing the non-destructive testing methods which require detailed pre-planning in advance of construction. CSL has already been specified in many foundations and TIP is likely to be specified more frequently in future due to the advantages described. Other methods are available and these are described in Recommendations on Piling (2012), ICE SPERW (2017), FHWA GEC (2010), and expert literature for non-destructive testing.

If testing of completed works is required, non-destructive testing (NDT) should be the first choice, in preference to destructive testing.

Direct Testing Methods

- Coring within the foundation to investigate features within the element, or to inspect the condition at the base. For the latter case, ducts may be installed attached to the reinforcing cage and extended to near the base to facilitate coring.
- Closed circuit television (CCTV) inspection of the foundation and its base, inside a drilled hole.
- Excavation to inspect the surface of the foundation.
- Extraction of a pile.

Cross-Hole Sonic Logging

Transmission of an acoustic wave from a transmitter embedded within a duct within the foundation element to a receiver positioned either in the same duct or a separate duct. The test method is detailed in ASTM D6760-14, and NF P94-160-1.

The time for the wave to reach the receiver and the energy transmitted is measured and used to interpret the result. In most applications, strong anomalies in travel time combined with decreased energy are interpreted as ultrasonic anomalies (potential defects, flaws).

The ducts for the sonic logging are typically located in an array within the reinforcing cage of the foundation, in order not to obstruct concrete flow. The ability to obtain sonic profiles between multiple pairs of tubes may provide an indication of the nature, position and dimension of a possible defect within the centre of the reinforcing cage and around the duct. It cannot provide any indication of possible defects in the cover zone, i.e. between the reinforcing cage and the face of the excavation.

The test is sensitive to variations in both the actual velocity within the concrete and the accuracy of duct positioning, and interpretation as well as assessment needs expert knowledge and should include all available information related to execution. (Beckhaus and Heinzelmann, 2015)

Thermal Integrity Profiling

Thermal integrity profiling (TIP) involves measuring the heat of hydration of the concrete. The differences in thermal conductivity and heat generation of any inclusions produce a variation in temperature that can be measured one or two days after pouring. The test method is detailed in US standard ASTM D7949-14. Fibre optic testing information is given in SPERW (2017).

The temperatures can be monitored by strings of thermistors, distributed fibre optic sensing methods or, occasionally, thermal probes are used, guided in tubes within the foundation element. These systems are generally attached to the reinforcement cage and so measure the temperature in the cover zone of the foundation element. Intellectual Property rights may apply to different proprietary systems.

In most applications, lack of increase in temperature could indicate a local thermal anomaly (potential defect). The thermal data can be acquired throughout the shaft, allowing for a full 3 dimensional analysis to be undertaken. The system can evaluate both the core of the shaft as well as the cover zone and can also give information on over-break, ground conditions and alignment of the reinforcement.

This technology can also be used to track concrete flow within the pile or panel during the tremie concrete process by monitoring the difference in temperature between the support fluid and concrete in real time.

Appendix D – Interpretation of Imperfections

Imperfections within a deep foundation element, which by definition deviate from the design quality and/or regular continuity of the cast in-situ concrete element, are considered as possible defects and are usually subject to further inspection. Imperfections are also referred to as features.

Imperfections are not necessarily defects. For example, marks in the concrete surface of piles from withdrawn excavation tools are inevitable (*see Figure D.1*). Such grooves should not be considered as imperfections, as long as they do not compromise the structurally required minimum cover after execution.

Figure D.1: Examples for piles with grooves, not affecting the minimum cover for durability

A thorough interpretation of imperfections should be conducted by an experienced specialist in geotechnical works who can then objectively assess whether the imperfection constitutes a defect or just an anomaly without causing adverse effect on bearing capacity or durability. The following sections may assist in interpreting and assessing imperfections.

The Formation Mechanism of Imperfections

For classification of imperfections, special features can reveal their formation mechanism although it is often the case that imperfections do not have a single cause and that is why specialist knowledge and experience is required:-

- Location of imperfections – related to dense reinforcement or obstructions in the cover zone?
- Limitation of imperfections – variation of cover thickness related to the occurrence?
- Type of material entrapped – mixture of material or solely comprised of concrete materials?
- Irregularities during placement – concrete placement and tremie pipe embedment records reveal issues during construction?
- Insufficient workability time – retarder dosage according to flow retention specified?
- Instability of concrete – Presence of a thick interface layer of material rising on top of the concrete, channel features on the exposed face, lack of aggregate in concrete?

Direct Inspection of Exposed Deep Foundations

After excavation the concrete surface anomalies can be assessed visually and photographed, for documentation.

Cores can be taken through assumed imperfections to assess their extent and to inspect the bond between the reinforcement and the concrete. Cores can be subjected to further testing or petrographic analysis to understand more about the concrete quality.

Indirect Inspection of Deep Foundations

Indirect inspection is referred to non-destructive testing and evaluation of signals, such as cross-hole sonic logging or thermal integrity profiling. Requires detailed pre-planning with the contractor enolved.

Classification of Type of Imperfections

Once imperfections are interpreted as systematic, they should be classified. Most imperfections will fall into one of the following three categories:-

Inclusions

Inclusions consist of entrapped material within the foundation that does not conform to the reference concrete. It can be uncemented material originating from a mixture of the support fluid, excavated material and the concrete, such as from the interface layer, or poorly cemented material originated from segregated concrete. Two examples are shown in Figure D.2.

Figure D.2: Examples of inclusions of a diaphragm wall and a pile (pile photo taken from Figure 9.14b, FHWA GEC10)

Inclusions are usually considered acceptable if limited in their extent and frequency. Only if these are of such dimensions that they are affecting the bearing capacity, or occupy wide parts in the cover zone and can therefore reduce durability, should inclusions be classified as defects. Non-destructive testing can assist in identifying inclusions (see Appendix C). These tests need special knowledge and experience with which the imperfection’s extent might be assessed by further evaluations.

Channelling

Channelling is also referred to as bleed channels. These are vertical narrow zones with lightly cemented aggregate with a lack of fines and cement matrix, usually near the surface of the panel or pile. This phenomenon is due to an insufficient stability of the concrete (poor segregation/bleeding resistance) for the actual ground and placement conditions.

Bleed channels are usually not considered defects if they are isolated and of limited thickness, thus not reducing the durability significantly (see figure D.3). In addition, bleed water can pass up around vertical installations within the cross-sections e.g. vertical reinforcement bars, or within the core of wide elements.

Figure D.3: Examples of channels running up the surface of a pile and a diaphragm wall

Mattressing

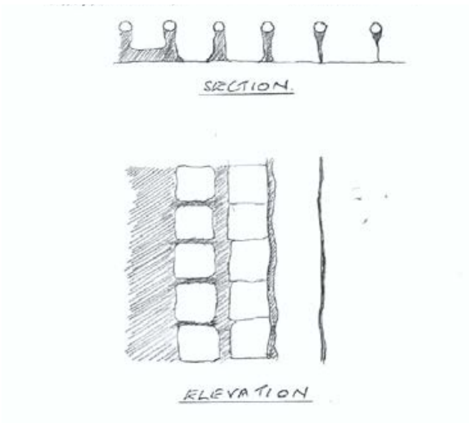
Whereas light mattressing describes vertical linear features emanating primarily from vertical reinforcing bars, heavier more pronounced mattressing reflects intersecting vertical and horizontal linear features. Both features emanate at the reinforcement with material trapped in the shadow of the reinforcing bars. Vertical mattressing features may provide a pre-defined route for bleed water leading to a combination of defects.

Mattressing can interrupt the entire depth of concrete cover to the reinforcement. As the effect on durability or bearing capacity (depending on the extent and frequency) can be significant, mattressing should be interpreted as a possible defect, and investigated further (see Figures D.4 and D.5).

The formation of mattressing is associated with restricted horizontal flow of concrete through reinforcement into the cover zone combined with insufficient vertical flow and therefore with a lack of free flow around reinforcement bars. The energy applied to the fresh concrete, its flow ability, stability and passing ability, in combination with the cage congestion and concrete cover dimension can all contribute to the extent of this imperfection. Mattressing is likely to be more prevalent at higher elevations where hydrostatic pressure is reduced.

Figure D.4: Shadowing in a pile (*left*); mattressing in a panel (*right*)

Figure D.5: Schematic showing varying degrees of mattressing



Appendix E – Detailed Information on Design Considerations

This Appendix should be read in conjunction with *Section 2* and includes supplementary information on detailing, concrete cover, single columns on single piles, all related to the impact on concrete flow.

Detailing

The detailing of deep foundation structures should only be carried out by experienced personnel.

Every effort must be made to ensure that reinforcement is not congested and satisfies the minimum clear spacing rules as given in relevant standards. Where a high density of reinforcement is required the maximum available bar diameter and maximum bar spacing should be used. Where multiple layers are needed special focus must be given to the maintenance of sufficient concrete flow (*see sections 3 and 6*). It is often the case that very dense reinforcement indicates that the dimensions of the deep foundation element need to be increased.

Additional constraints on reinforcing cage layout also include:-

- Additional reinforcement to allow lifting and placing (e.g. stirrups and cross-bracings)
- Space for the stop end (where used)
- Space for the tremie pipe
- Instrumentation
- Width and length constraints due to transportation restrictions
- The weight of the reinforcement cage
- Items in the cover zone such as spacers, box outs or couplers
- Tie-back sleeves and other embedded items such as utility blockouts, etc.

Detailing requirements for cages are summarized in *Tables E.1, E.2 and E.3.*

Structural codes like EN 1992 set general normative regulations for the detailing, in particular for the spacing and the concrete cover of structural elements. These are also valid for deep foundations i.e. for their structural design. Execution tolerances, such as the dimensions of the reinforcement cage, are considered, but these cannot cover all the specific tolerances for deep foundations. Subsequently, execution standards like EN 1536 and EN 1538 set additional regulations, leading sometimes to conflicting interpretations.

Reinforcement Clear Spacing

The clear spacing between reinforcement bars affects the ability of concrete to flow into the cover zone, and must be appropriate for the actual conditions. This is difficult to quantify as it requires consideration of the spacing between horizontal and vertical bars, clear window size, the layout of multiple rows of reinforcement, the concrete aggregate size, and the rheology in connection with flow distances and hydrostatic pressures. Transverse reinforcement which runs through the centre of the reinforcing cage, (couplers, links, tie rods etc.) affects the vertical upward flow of the concrete.

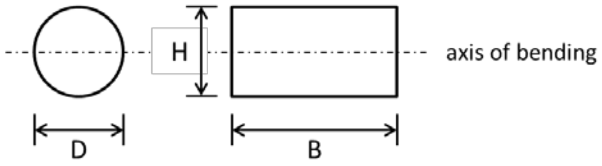
There is consensus that spacing of reinforcement bars for deep foundations shall be much higher than required by the structural codes, due to onerous execution requirements.

As set out in section 2.2, a minimum clear spacing on vertical of 100 mm should be mandatory, FHWA GEC10 recommends values from 5 to 10 times the maximum aggregate size for difficult installation conditions i.e. very large or very deep elements, multiple bar layers and intricate cage geometry. This also includes splice zones or where bars are connected with couplers.

It is hoped that future research by computational simulations, validated by field trials, may assist in establishing clearer rules for the appropriate clear spacing.

TABLE E.1: Commonly used reinforcement requirements for Bored Piles and Barrettes

Minimum reinforcement
for bored piles and barrettes



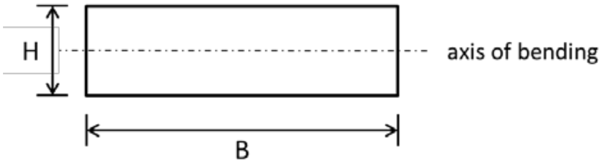
Location	**Clause**	**Value**	**Comments**	
For elements where the load eccentricity does not exceed D/8 for piles, or H/6 for barrettes				
Vertical	ACI336.3R-14, 4.6, referring to ACI318 (see ACI318-14, 10.6.1)	1% A_c	for elements in compression that cannot be designed as plain concrete, where A_c is nominal cross section.	
	EN1536:2010+A1, Table 5	≥ 0.5% A_c	$A_c \leq 0.5\ m^2$	where A_c is nominal bored pile cross section
		≥ 0.0025 m^2	$0.5\ m^2 < A_c \leq 1.0\ m^2$	
		≥ 0.25% A_c	$A_c > 1.0\ m^2$	
Links, hoops or spiral reinforcement	ACI336.3R-14, 4.6 referring to ACI318 (see ACI318-14, 10.6.1)		ACI318-14, 10.6.2.2 gives minimum area of spiral reinforcement	
	EN1536:2010+A1, Table 6	≥ 6 mm ≥ one quarter of the maximum diameter of the longitudinal bars	links, hoops or spiral reinforcement	
		≥ 5 mm	wires of welded mesh transverse reinforcement	
For elements where the load eccentricity exceeds D/8 for piles, or H/6 for barrettes				
Vertical	EN1992-1-1:2004+A1, 9.3.1	$(f_{cm}/f_{yk})\ A_c$, but not less than 0.5% A_c	where f_{cm} is the mean strength of the concrete, which can be taken as 8 MPa higher than the characteristic strength, and f_{yk} is the yield strength of the reinforcement (these expressions assume just over one quarter of the reinforcement controls the cracking on the tensile face)	
Links, hoops or spiral reinforcement (where required for shear strength)	EN1992-1-1:2004+A1, 9.2.2	area of link or spiral reinforcement for pile ≥ $0.08\ [f_{ck}]^{1/2}/f_{yk}$ area of link for barrette ≥ $0.08\ [f_{ck}]^{1/2}/f_{yk}$	where s is the spacing of the links or pitch of the spiral reinforcement, f_{ck} is the characteristic strength of the concrete (N/mm²), f_{yk} is the yield strength of the reinforcement	
	EN1992-1-1:2004+A1, 9.2.2	vertical spacing of links for piles ≤ 0.6 D vertical spacing of links for barrettes ≤ 0.6 H pitch of spiral reinforcement ≤ 0.3 D	(this assumes that the effective depth is around 0.8 D for piles or 0.8 H for barrettes and that the potential failure plane intersects spiral reinforcement at least three times)	

TABLE E.1: Commonly used reinforcement requirements for Bored Piles and Barrettes (continued)

Clear spacing for bored piles and barrettes			
Location	**Clause**	**Value**	**Comments**
Horizontal and vertical spacing of bars	ACI336.1-01, 3.4.9	≥ 100 mm	including at laps.
	ACI336.1-01, 3.4.9	≥ 4 D_{max}	where D_{max} = maximum aggregate size, including at laps.
	EN1536:2010+A1, 7.5.2.5	≤ 400 mm	as wide as possible, but less than 400 mm.
	EN206:2013+A1, Annex D.2.2	≥ 4 D_{max}	where D_{max} = maximum aggregate size.
	EN1536:2010+A1, 7.5.2.6	≥ 100 mm	for single or bundles of longitudinal bars.
	EN1536:2010+A1, 7.5.2.7	≥ 80 mm	for lap length, provided that D_G ≤ 20mm (special consideration must be given to the maintenance of sufficient concrete flow, see sections 3 and 6).
	EN1536:2010+A1, 7.5.2.9	≥ 1.5 D_{max} and ≥ 2.0 D_S	for layers of bars, placed radially, where D_S is the (steel) bar diameter.

TABLE E.2: Commonly used reinforcement requirements for Diaphragm Walls

Minimum reinforcement for diaphragm walls



Location	**Clause**	**Value**	**Comment**
Vertical - for walls where the load eccentricity does not exceed H/6	EN1992-1-1:2004+A1, 9.6.2	0.2% A_c	where A_c is nominal area of panel
	EN1538:2010+A1, 7.5.3.1	$D_s \geq 12$ mm	where D_s is the (steel) bar diameter
	EN1538:2010+A1, 7.5.3.1	> 3 bars / m	
Vertical - for walls where the load eccentricity exceeds H/6	EN1992-1-1:2004+A1, 9.3.1	minimum area in each face / unit length = 0.26 (f_{cm}/f_{yk}) d, but not less than 0.0013 d	where f_{cm} is the mean strength of the concrete, which can be taken as 8 N/mm² higher than the characteristic strength, f_{yk} is the yield strength of the reinforcement, and d is the effective depth to the centroid of the tension reinforcement from the compression face
	EN1538:2010+A1, 7.5.3.1	$D_s \geq 12$ mm	where D_s = (steel) bar diameter
	EN1538:2010+A1, 7.5.3.1	> 3 bars / m	
Horizontal	EN1992-1-1:2004+A1, 9.6.3	minimum total area / unit height > 0.1% A_c	where A_c is nominal area of vertical section through panel / unit height
	EN1992-1-1:2004+A1, 9.6.3	minimum area in each face / unit height ≥ 25% A_{sv}	where A_{sv} is the area of vertical reinforcement in face / unit length
	EN1538:2010+A1		no specific requirements
Through-thickness links (where required for shear strength)	EN1992-1-1:2004+A1, 9.2.2	minimum area / unit area of wall (in elevation) $(0.08\ [f_{ck}]^{1/2})/f_{yk}$	where f_{ck} is the characteristic strength of the concrete, f_{yk} is the yield strength of the reinforcement
	EN1992-1-1:2004+A1, 9.2.2	horizontal spacing ≤ 0.75 d, but not more than 600 mm	where d is the effective depth to the centroid of the tension reinforcement from the compression face
	EN1992-1-1:2004+A1, 9.2.2	vertical spacing ≤ 0.75 d	

TABLE E.2: Commonly used reinforcement requirements for Diaphragm Walls (continued)

CLEAR SPACING FOR DIAPHRAGM WALLS			
LOCATION	**CLAUSE**	**VALUE**	**COMMENT**
spacing of vertical bars	EN206:2013+A1, Annex D.2.2	≥ 4 D_{max}	where D_{max} is the maximum aggregate size.
	EN1538:2010+A1, 7.5.3.2	≥ 100 mm	of single bars or groups, parallel to the wall face.
	EN1538:2010+A1, 7.5.3.3	≥ 80 mm	for the lap length, provided that $D_{max} \leq 20mm$ (special consideration must be given to the maintenance of sufficient concrete flow, see sections 3 and 6).
spacing of horizontal bars	EN1538:2010+A1, 7.5.4.2	≥ 200 mm	
	EN1538:2010+A1, 7.5.4.3	≥ 150 mm	where required, provided that $D_{max} \leq 20mm$, where D_{max} is the maximum aggregate size.
spacing of horizontal bars	EN1538:2010+A1, 7.5.4.4	≥ 150 mm	
horizontal spacing of adjacent cages	EN1538:2010+A1, 7.5.5.1	≥ 200 mm	
	EN1538:2010+A1, 7.5.5.2	≥ 400 mm	recommended
horizontal spacing of cages and joints incl. water-ends	EN1538:2010+A1, 7.5.5.3	≥ 100 mm	
	EN1538:2010+A1, 7.5.5.4	≥ 200 mm	recommended

TABLE E.3: Common requirements for bond, anchorage, laps and crack width

<table>
<tr><th colspan="3">BOND, ANCHORAGE (DEVELOPMENT LENGTHS) AND LAPS (SPLICE LENGTHS) FOR BORED PILES AND DIAPHRAGM WALLS</th></tr>
<tr><th>LOCATION</th><th>CLAUSE</th><th>COMMENT</th></tr>
<tr><td>Anchorage</td><td>ACI318-14, 25.4.2
ACI318-14, 25.4.9</td><td>Bars in tension.
Bars in compression.</td></tr>
<tr><td>Lap length</td><td>ACI318-14, 25.5.2
ACI318-14, 25.5.5
ACI318-14, 25.6
ACI318-14, 10.7.5.2</td><td>Bars in tension.
Bars in compression.
Additional rules for bundled bars.
Additional rules for columns, which are assumed to apply also to piles.</td></tr>
<tr><td>Bond strength</td><td>EN1992-1-1:2004+A1, 8.4.2</td><td>If support fluid has not been used, bond conditions would normally be classified as ‘good’ for both vertical and horizontal bars. Specialist advice (e.g., Jones and Holt, 2004) should be sought on the impact on bond of support fluids.</td></tr>
<tr><td>Anchorage length</td><td>EN1992-1-1:2004+A1, 8.4.4</td><td>Note that where the cover exceeds the bar size, which will usually be the case, the factor α_2 can be taken as less than unity.</td></tr>
<tr><td>Lap length</td><td>EN1992-1-1:2004+A1, 8.7.3</td><td>Note that where the cover exceeds the bar size, which will usually be the case, the factor α_2 can be taken as less than unity. The factor α_6, however, will usually be 1.5, corresponding to all bars being lapped at one location. The use of couplers should be considered, particularly for large bars, which EN1992-1-1, 8.8 specifies as having a diameter larger than 32mm (40mm in the UK NA).</td></tr>
<tr><th colspan="3">CRACK WIDTHS</th></tr>
<tr><th>LOCATION</th><th>CLAUSE</th><th>COMMENT</th></tr>
<tr><td rowspan="2">Calculation of crack widths</td><td>ACI336.3R-14</td><td>No requirements</td></tr>
<tr><td>EN1992-1-1:2004+A1,7.3.4</td><td>Note that the comments under Table NA.4 in the UK National Annex to EN1992-1-1, include guidance for situations where the cover is significantly greater than that required for durability, and there are no appearance requirements, such as structures cast against ground. Under these circumstances, it is reasonable to determine the crack width at the cover required for durability, and to verify that it does not exceed the relevant maximum crack width. This may be done by assuming that the crack width varies linearly from zero width at the face of the bar, to the calculated value at the surface.</td></tr>
</table>

Concrete Cover

In terms of structural requirements, cover is required both for durability and to provide resistance to the splitting forces generated by the reinforcement bond.

For execution of deep foundations using concrete placed by tremie, provision of a suitable amount of cover, as stated in execution standards (EN 1536 and EN 1538, ACI 301), is critical to allow the concrete to flow around and completely embed the reinforcement bars to obtain dense durable concrete in this cover zone.

The greater of the individual minimum values for cover required from considerations of bond, durability and execution should be increased by an allowance for construction tolerance as shown in section 2.3, and below.

Nominal cover = greater of minimum required for cover for durability, bond, execution + allowance for construction tolerance:

$$c_{nom} = c_{min} + \Delta c_{dev} \quad \text{with} \quad c_{min} \geq \max \begin{bmatrix} c_{min,structural} \\ c_{min,execution} \end{bmatrix}$$

The general recommendation of this Guide is that the minimum nominal cover for execution should be 75 mm [3in] i.e. a minimum cover of 50 mm [2 in] plus a tolerance of 25 mm [1 in].

The nominal cover should be increased in cases where the structural minimum cover e.g. as given in EN 1992, is greater than 50 mm (as given above) by the corresponding amount.

Note 1: The minimum cover for execution should be increased if the conditions for concrete flow are considered critical. Some examples are given in EN 1536 such as where a large maximum grain size of 32 mm [1 ¼ in] is used or if the concrete viscosity is increased (e.g. where silica fume replaces cement by a considerable fraction of 5% or greater), or in soft soil without the use of a casing.

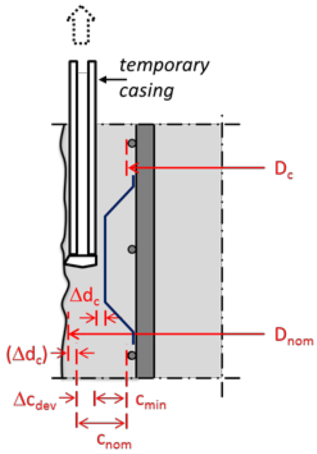
Note 2: FHWA GEC 10 (2010) suggests higher cover for larger diameter shafts i.e. 3 in (75 mm) cover for shafts of diameter not greater than 3 ft (1 m), 4 in (100 mm) cover for diameter greater than 3 ft but not greater than 5 ft (1.5 m), and 6 in (150 mm) cover for diameter above 5 ft.

Note 3: EN 1536 permits the minimum concrete cover for execution to be reduced to 40 mm to the external face of a permanent casing or lining, where used. It is recommended that the minimum cover of the reinforcement cage to the inner face of a casing, both temporary and permanent, should not be less than 50 mm. An allowance for construction tolerances is not required in this case, but an additional tolerance for cage installation is still compulsory, see Figure E.1.

Note 4: The required distance between cages and joints or formwork ends are independent of the concrete cover. In accordance with EN 1538:2010+A1, 7.5.5.3 and 7.5.5.4 these distances should be ≥ 100 mm and ≤ 200 mm respectively.

Note 5: Many designers are reluctant to apply a large concrete cover on the basis that the crack width at the face may become excessive. This should not be a concern as crack width should only be calculated at the minimum cover position, with concrete outside that value being considered as surplus (see CIRIA Guide C760 (2017) and ACI 350).

Figure E.1: Concrete cover in bored piles supported by a temporary casing (supplementing Fig. 3)



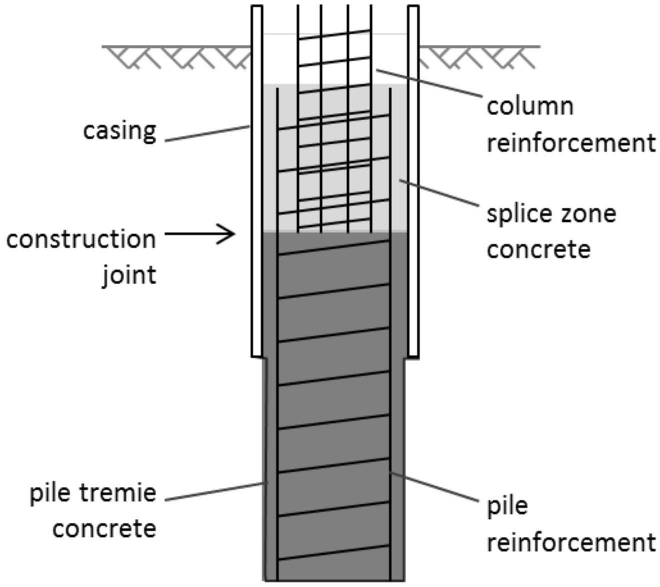
Single Columns on Single Piles

Cage connection details can present a challenge for constructability for bored piles where a single bored pile is used to support a single column and the splice between the column and pile reinforcement occurs near the top of the pile. This detail can be particularly congested where a non-contact lap splice is used and the column reinforcement comprises a separate cage within the pile reinforcement as shown on *Figure E.2*. Anchor bolt connections to transmission towers, sign poles, or similar structures also can result in congestion of this type. It is especially difficult for tremie concrete to make its way through two reinforcing cages without trapping fluid contaminants at the very top of the pile.

The most effective solution for this situation is to provide for a construction joint at a location below the splice, so that the pile head can be trimmed and the concrete at the splice connection can be cast in the dry as conventional structural concrete. This approach typically requires that a surface casing be used to provide a stable pile excavation above the construction joint. The surface of the construction joint would typically require preparation by removing any laitance, bleed water, or contaminated concrete prior to concrete placement at the splice. In some cases it may be possible to remove fluids and contaminated concrete within the splice zone and complete the splice while the concrete remains workable.

In some cases where the overlap into the pile is relatively short (e.g. up to 2 m), it may be possible to insert the inner cage into the fresh concrete after the concrete placement has been completed. Although this approach would be unwieldy with a tall column cage, it may be manageable with a short section of reinforcement used to extend above grade as a splice cage or for an anchor bolt assembly. This process (commonly referred to as “wet-sticking”) can have limitations if alignment tolerances are tight because of difficulties in precise placement and the short time window in which the concrete remains sufficiently flowable for the work to be completed.

Figure E.2: Connection details for a bored pile used to support a superstructure column



Appendix F – Selection of Factors and Effects on Concrete Flow

A selection of important factors and their possible effects on concrete flow within a deep foundation, and on the associated quality, is shown in Table F.1. This Table reflects the common understanding of the Concrete Task Group. The list is not exhaustive, but allows a broad overview of the contents of this Guide.

Table F.1: Various factors and their possible effects on concrete flow and quality of deep foundations

Parameter	Recommendation	Effect(s)	See
Clear reinforcement spacing	Maximise	Less blocking resistance and less resistance to concrete passing through. Minimise the risk of bentonite inclusions and insufficient embedment of the reinforcement bars by concrete.	2.2, App. E 6.8
Multiple layer reinforcement	Avoid	Less resistance to concrete passing through.	2.2
Concrete cover	Increase	Reduces risk for shadowing or mattressing and may act as a safety margin for an unavoidable filter cake thickness.	2.2
Concrete rheology and workability	Medium/low yield stress Medium viscosity	High yield and high viscosity lead to poor flowability. Too low yield stress can cause instability. High variations in properties may contribute to irregular flow patterns.	3.2 4.3 6.7
Thixotropy	Control	Excessive increase in yield stress of concrete during unavoidable resting times may contribute to irregular flow patterns. In concrete finally placed the same effect would lead to less filtration, bleeding or segregation	3.2
Concrete stability	Control	Excessive filtration, bleeding or segregation can lead to irregular flow patterns, and to anomalies.	3.3
Use of additions and (chemical) admixtures	Optimise	Enhances rheology. Might affect robustness and stability of the concrete mix (depending on proportioning and interaction with other).	4.4
Slump flow	As per Table 5.1	Higher values lead to better workability but less stability.	5.1
Slump flow velocity	As per Table 5.1	Lower values lead to higher resistance to flow which may increase total pouring times.	5.1
Suitability testing	Laboratory trials at design stage Repeat	Finding suitable composition with available materials to meet the project specific requirements on concrete, allowing directions for specifying conformity values. Proving suitability with changes of materials or dosages.	5.2
Conformity testing	Field trials at start of execution Adapt mix design	Confirming that properties, specified at design stage, can be achieved with the actual concrete from the supplier. Allowing conformity with designed performance by small changes in mix design; repeat suitability testing otherwise.	5.2
Acceptance testing	Frequently during execution	Proving conformity with specifications on a regular basis, and complying with QC regulations.	5.2
Workability retention	Control	Allowing still workable concrete at the end of designed pouring time. An excessive increase in yield stress should be	5.3

		avoided as it may lead to insufficient workability. Longer retention may increase bleeding and segregation.	
Total pour time	Minimise delays	Less change in rheology of the concrete	5.3
Debris on base	Limit	Debris at the base can contribute to mixing with the initial concrete load and to inclusions.	6.2
Density of support fluid	Limit	Less resistance to concrete flow.	6.2
Cleanliness of support fluid	Maximise	More soil particles in the support fluid may contribute to a thicker interface layer on top of the concrete.	6.2
Tremie pipe surface	Smooth and clean	Limits the friction between concrete and tremie pipe, and the restriction to flow	6.3
Tremie spacing	Limit	Longer flow distance can cause problems near the reinforcement cage, in the cover zone or near the joints	6.4 6.8
Tremie embedment	Minimise	Faster concrete flow. Earlier cessation of movement in (finally placed) concrete below the tremie pipe. Reduced risk of dynamic segregation.	6.6
Volcano flow	-	Reduces need for workability retention. Requires less workability retention, leading to less dosage of admixture and less sensitive mixes.	6.7
Plug flow	-	Contributes to increasing the yield stress by thixotropy due to no internal shearing.	6.7
Variations in workability of individual loads	Limit	High variations may lead to a change of flow mechanism, and can contribute to irregular flow patterns.	9

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