EFFC/DFI

Best Practice Guide to Tremie Concrete for Deep Foundations

by joint EFFC/DFI Concrete Task Group

1st Edition, 2015

EFFC

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DEEP FOUNDATIONS INSTITUTE

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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), Type II) latent hydraulic or pozzolanic (SCM).
admixture, chemical	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 cast-in-place reinforced concrete column. A barrette can also be defined as a rectangular diaphragm wall element that is being used as a deep foundation.
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 material which, when mixed with water, forms a paste that sets and hardens by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water
Bingham fluid	fluid with non-zero yield stress
bored pile (drilled shaft)	cast in place, usually circular cross section concrete column (or pile), see figure 1
bleeding	form of segregation in which some of the water in the mix tends to rise to the surface of freshly placed concrete
clear spacing	minimum space between singular reinforcement bars or bundles of bars, i.e. opening for the concrete to flow through
consistence	relative mobility, or ability of freshly mixed concrete to flow, i.e. an indication for workability
cover	distance between the outside of the reinforcement and the nearest concrete face
deep foundation	foundation type which transfers structural load through layers of weak ground onto suitable bearing strata (piles and barrettes); also refers to specialist retaining walls such as diaphragm walls and secant pile walls
diaphragm wall	reinforced cast in place concrete wall normally consisting of a series of discrete abutting panels, 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 de-filtered material, such as bentonite and excavated soil in suspension, built up in the transition zone to a permeable medium, by water drainage due to pressure
filtration	mechanism of separating fluids (mixing water or cement paste) from concrete which has not yet fully hydrated, where the surrounding, permeable ground under hydrostatic pressure is acting as a filter
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 still in a condition that is capable of being compacted by the chosen method, see tremie concrete
panel	section of a diaphragm wall which 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
plastic viscosity	viscosity of a Bingham Fluid (with non-zero shear stress)
rheology	science of deformation and flow of substances subject to shear
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 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 former, 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 drilled shaft
thixotropy	the tendency of a material to progressive loss of fluidity when allowed to rest undisturbed but to regain its fluidity when shear stress is applied
tremie concrete	concrete with the ability to achieve full compaction by self weight when placed by tremie in a deep foundation, under submerged conditions
tremie pipe / tremie	segmental pipe with waterproof joints topped by a hopper
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	that 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 specified duration
yield stress	shear stress required to be reached to initiate flow

List of Abbreviations and Symbols

AASHTO   American Association of State and Highway Transportation Officials
ACI   American Concrete Institute
AFNOR   Association Francaise de Normalisation
API   American Petroleum Institute
ASTM   ASTM International, until 2012: American Society for Testing and Materials
CIA   Concrete Institute of Australia
CIRIA   Construction Industry Research and Information Association
CEN   European Committee for Standardization
DFI   Deep Foundations Institute
EFFC   European Federation of Foundation Contractors
FHWA   Federal Highway Administration
ICE   Institution of Civil Engineers
ISO   International Organization for Standardization
ÖBV   Österreichische Bautechnik Vereinigung (en: Austrian Society for Construction Technology)

ECPC   Equivalent Concrete Performance Concept
EPCC   Equivalent Performance of Combinations Concept
GGBS   Ground granulated blast furnace slag
QA/QC   Quality Assurance/Quality Control
SCC   Self-Compacting Concrete
VSI   Visual Stability Index

c_{min} minimum concrete cover according to structural or execution codes
Δc_{dev} allowance in design for construction tolerance
c_{nom} nominal concrete cover = $c_{min} + \Delta c_{dev}$ (to be considered in design)
D dimension (diameter or thickness) of excavation or concrete element
D_{nom} nominal excavation dimension, defined by excavation tool dimensions
D_G maximum aggregate size
D_{final} final diameter of diameter of spread of concrete in slump test
D_s reinforcement bar diameter
D_T internal diameter of tremie pipe
d_{b-t} distance from bottom of excavation to tremie pipe outlet
η dynamic viscosity
H_2/H_1 relation between heights at relevant marks in the L-box test
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_0) and inside (p_1) the excavation
s_T section length of tremie pipe section to cut
T_x time for concrete to reach relevant marks (x = 200/400/500 mm) on the horizontal box in the L-box test
T_{end} time for concrete to reach the far end of the horizontal box in the L-box test
T_{final} time for concrete to reach final spread in slump test
τ shear stress
τ_0 yield stress
$\dot{\gamma}$ shear rate

FIGURE 1.0 - Examples of deep foundations
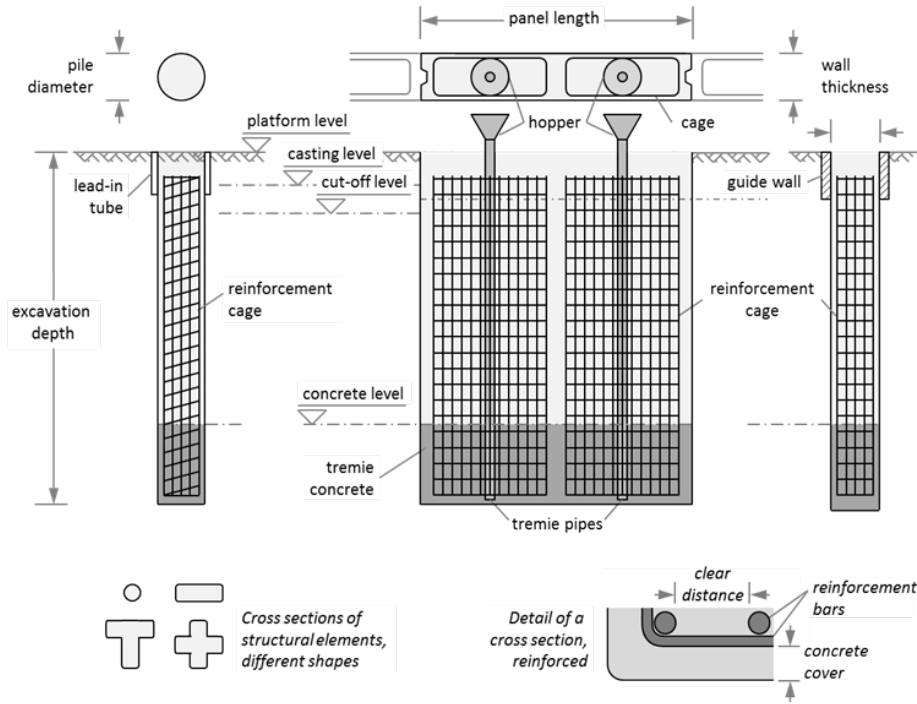
1   General

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 slump or flow table test to be used as the only acceptance test for the fresh concrete.

A 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 that many of the problems were caused by (or in part due to) the use of inadequate concrete mixes with inadequate workability, or insufficient stability or robustness of the mixes. The review identified the primary causes as inadequate concrete specifications and inadequate testing procedures. The consequences of these problems are often significant and it has been recognised that spending more on getting the concrete right is the most cost effective approach.

A joint Concrete Task Group was set up by EFFC and DFI in 2014 to look at this issue and this Guide is the output from that Task Group.

A research and development project, funded by the Sponsors of this Guide, is being carried out by the Technical University of Munich in conjunction with the Missouri University of Science and Technology. This project includes desk studies, laboratory testing, and onsite testing at worksites in Europe and the US. The research work will be completed during 2016.

1.2   Purpose and Scope

The primary purpose of this Guide is to give guidance on the characteristic performance of fresh concrete and its method of placement using tremie methods in bored piles and diaphragm walls, allowing construction of high quality elements. In addition, The Guide proposes changes to the methods used to specify the concrete mix, as well as the methods used to test the mix. The principles of this guide can also be used for other forms of deep foundations (e.g. continuous flight auger piling).

Concrete in deep foundations has to fulfil a number of demanding and often conflicting requirements that have to be considered throughout the whole evolution of a concrete mix, as summarised in *Figure 1.1.*

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, and this Guide highlights the important areas which require careful consideration in order to minimize the risks. Getting the mix right can only be achieved in a joint approach by 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 first edition of the Guide proposes appropriate performance criteria for the concrete together with test methods and initial recommendations on acceptance values. A second edition of the Guide will be published on completion of the research and development work as this will allow definitive acceptance criteria to be presented.

The Guide addresses design considerations including, concrete rheology, mix design, reinforcement detailing and concrete cover and best 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 results.

FIGURE 1.1 - typical evolution of concrete mixes for execution

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┌─────────────────────────────────────────────────┐
│ CLIENT: relevant codes and standards, service    │
│ life, other service/operational related          │
│ requirements                                      │
└─────────────────────────────────────────────────┘
                        ↓
┌─────────────────────────────────────────────────┐
│ STRUCTURAL DESIGN: dimensions, concrete strength, │
│ cover, reinforcement details, restrictions on     │
│ binder/other constituents, and water/cement ratio │
└─────────────────────────────────────────────────┘
                        ↓
┌─────────────────────────────────────────────────┐
│ CONSTRUCTOR: Fresh concrete properties relevant to│
│ execution, e.g. workability, early strength gain  │
└─────────────────────────────────────────────────┘
                        ↓
┌─────────────────────────────────────────────────┐
│ SPECIFIER: concrete specification                 │
│ (combines client's, structural design's, and      │
│ constructor's requirements)                        │
└─────────────────────────────────────────────────┘
                        ↓
┌─────────────────────────────────────────────────┐
│ SUPPLIER: concrete mix considering available      │
│ constituents and the specified requirements, e.g. │
│ consistence, bleed, setting time, early age       │
│ strength, target strength, shrinkage, supply rate │
│ ...                                               │
└─────────────────────────────────────────────────┘
                        ↓
┌─────────────────────────────────────────────────┐
│ EXECUTION                                         │
└─────────────────────────────────────────────────┘
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The Guide is aimed at those 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.

2   Design Considerations Impacting Concrete Flow

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 foundations. This section is limited to structural detailing and impact of the reinforcement cage on the tremie concrete flow in the cover zone. 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 1997-1:2004) or relevant American standards (FHWA GEC10, 2010).

With regards to the detailing, the ideal situation for tremie concrete placement is for there to be no obstructions to flow. The reinforcement cage, with spacer blocks and box-outs, represents a major obstruction to flow. Given that reinforcement is normally required to satisfy structural requirements, it follows that the structural design, including the design of the reinforcement cage, plays a key role in the quality of the finished pile/panel.

Regarding the concrete cover for deep foundations, there are two independent requirements to be considered in 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 and in particular to concrete flow.

These two approaches are independent and therefore not necessarily compatible. The designer should specify a nominal cover based on a minimum cover plus an allowance for construction tolerances.

A minimum nominal concrete cover of 75mm (3in) is recommended where the concrete is cast directly against the ground. Where casing is used and the excavation surface can be considered 'smooth', the minimum requirement may be reduced to 50mm (2 in). These values are shown in Figure 2.

In most cases, the minimum nominal values given above will exceed those derived from structural and durability requirements. EN 1536:2010 Clause 7.7.3 identifies particular instances where the minimum nominal cover may need to be increased and these rules should be followed.

FIGURE 2 – *concrete cover requirements for execution in deep foundations*
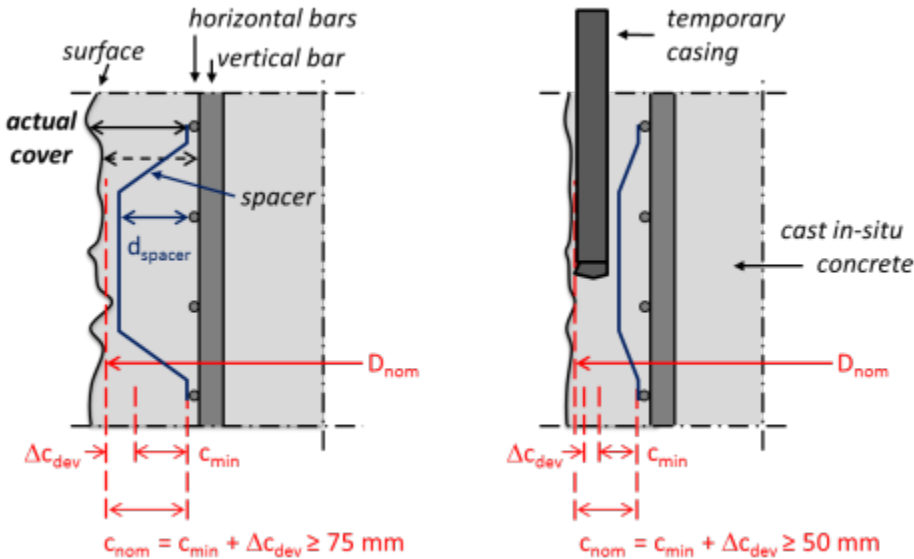
More detailed information on design considerations is given in *Appendix F*.

# 3 Rheology 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. The key rheological characteristics are:-

- Workability or flow (the general term defining the ability of the concrete to fill the excavation, flow around obstacles and compact by gravity)
- Flow 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. Concretes are designed considering durability in addition to strength and the tendency is 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, where 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 3.1.

FIGURE 3.1 – *Dependencies between composition, rheology and related characteristics, and overall requirements*
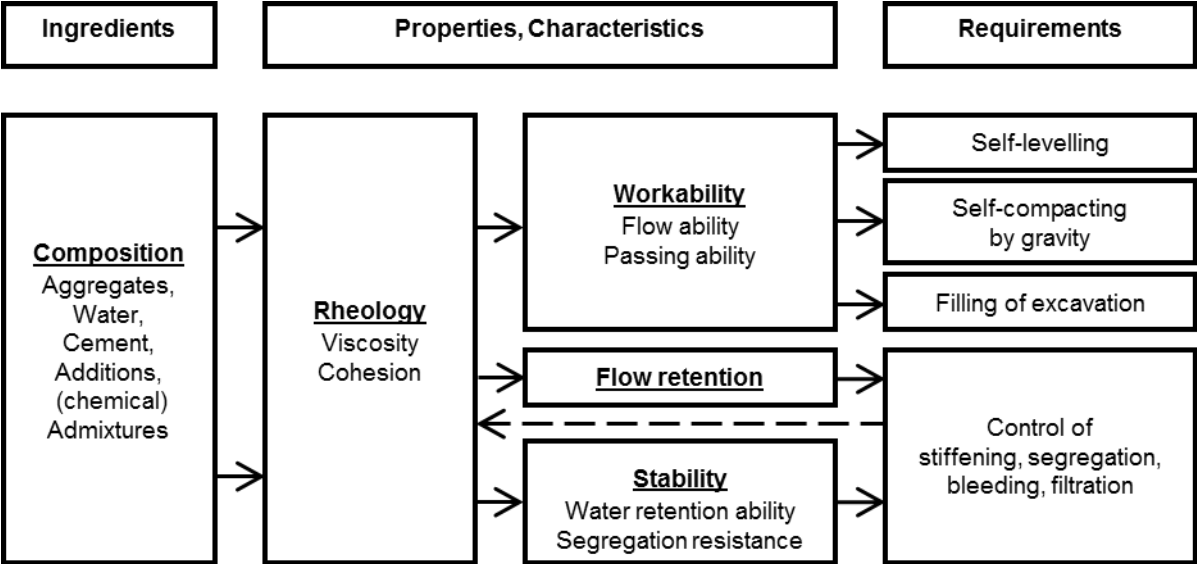
There is very little guidance in current standards on the assessment of rheological behaviour. This chapter provides an explanation of concrete rheology and key parameters used to identify rheology.

3.2   Rheology

To properly understand the behaviour of concrete in a fresh state it is necessary to define certain parameters:
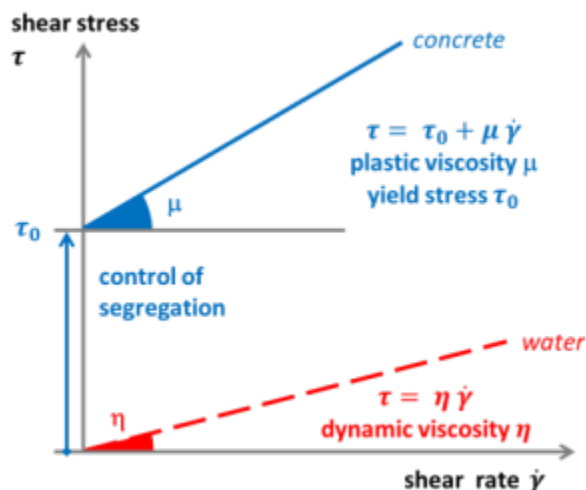
- The yield stress, τ_0
- The plastic viscosity, μ

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

Plastic viscosity is the viscosity of a Bingham fluid 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 truck.

Figure 3.2 describes with a simplified graph, that concrete requires a certain amount of energy to start moving (the yield stress) and, thereafter, it resists this movement (by viscosity).

FIGURE 3.2 - plastic behaviour of a Bingham fluid (e.g. concrete) versus a Newtonion 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 measured correctly with laboratory apparatus (rheometer). Until now, the ease of flow – as a measure for viscosity – has been assessed intuitively and qualitatively during placement, for example, through observing and classifying the difficulty of emptying the tremies or truck unloading times.

Figure 3.3 illustrates a qualitative comparison of yield stress and viscosity for different concrete types and applications. Normal concrete, compacted using vibrators, has both a high yield stress and high viscosity. Self-compacting concrete requires very low yield stress for self-levelling and compacting by self-weight alone. Tremie concrete needs a low viscosity for a good filling ability at a relatively high cohesion (represented by the yield stress value) for undisturbed displacing of support fluid and controlling segregation in deep foundations. As a benefit the large concrete head assists in compaction and makes it unnecessary to work at very low yield stress values which might result in sensitive concrete mixes.

FIGURE 3.3 - comparison of concrete types
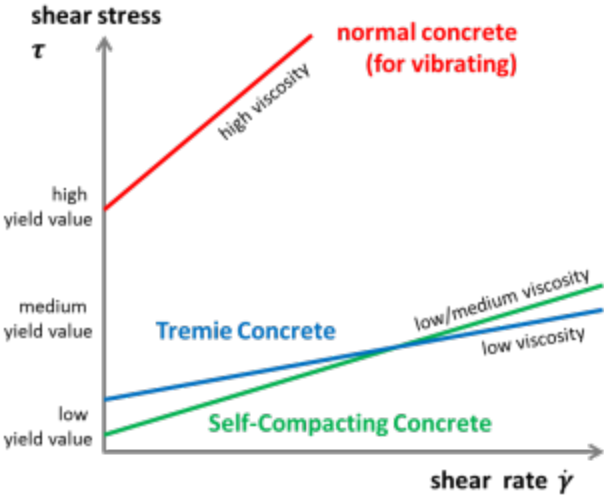
Concrete is considered a thixotropic material, in the fresh state, it exhibits a form of stiffening which is reversible and fluidity is regained when the material is agitated.

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, this is illustrated in *Figure 3.4* (Roussel, 2012).

FIGURE 3.4 – stiffening and setting time
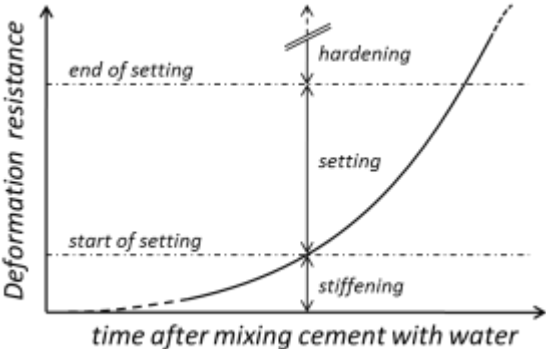
4 Mix Design

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' (Neville and Brooks, 2010).

The comments contained within 4.2, 4.3 and 4.4 are intended to highlight critical issues which are relevant to tremie concrete.

4.2 Mix design considerations

A successful concrete mix design must meet the requirements of fresh and hardened properties 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 proportioning is a complex process balancing the requirements of the specification with concrete behaviour and performance. The process for mix constituent selection and proportioning and final mix validation should consider the following:-

- 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 will consider the following:

- Compressive strength and durability (or 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 (see Appendix C for details)
- Free water content
- Water/binder 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 complied with, e.g. a limited chloride diffusion coefficient. A subsequent demand for special constituents, higher dosages of super-fine additions, an extra low water/binder ratio or similar will in turn affect the fresh concrete properties. Opposing effects on durability and workability have to be balanced.

4.3   Materials

Concrete rheology is affected by aggregate properties, particle shape and size distribution, binder content, water binder ratio and admixture type and dose.

The influence of cementitious additions on the rheological behaviour of concrete is shown to the left in *Figure 4.1,* 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 4.1,* (Wallevik, 2003).

FIGURE 4.1 - influence of cement and other components on rheology, acc. to Wallevik (2003)
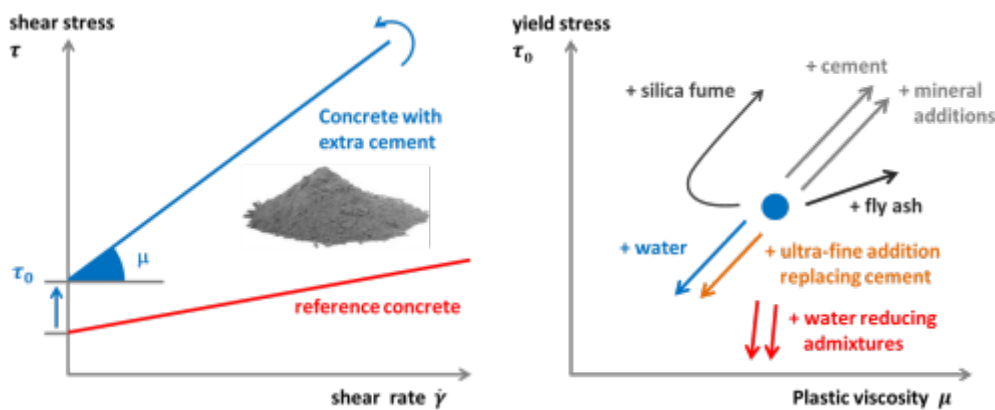
A concrete mix must obey the requirements of standards and specifications in place, and must remain within the acceptable range dictated by the specified w/c-ratio, fines content, minimum compressive strength etc.

However, 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 an excessive concrete sensitivity to small variations in water content, 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, 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.
- Add a viscosity modifying admixture.

Note: Silica fume can play a special role in that it can sometimes be 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 at higher percentages.

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 size of particles. In order to minimise the risk or tendency for segregation, aggregates should be well graded and round aggregates are preferred.

Figure 4.2 and Figure 4.3 both illustrate sieve curves for a maximum aggregate size of 20 and 22 mm [3/4 in] respectively, following the general recommendation to optimise the aggregate packing density.

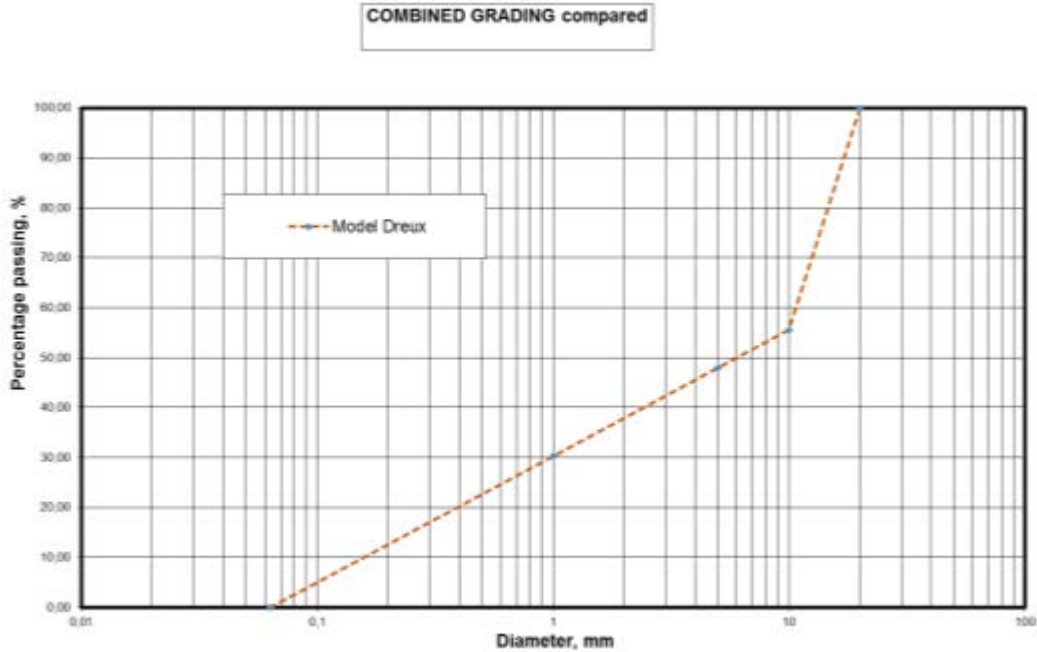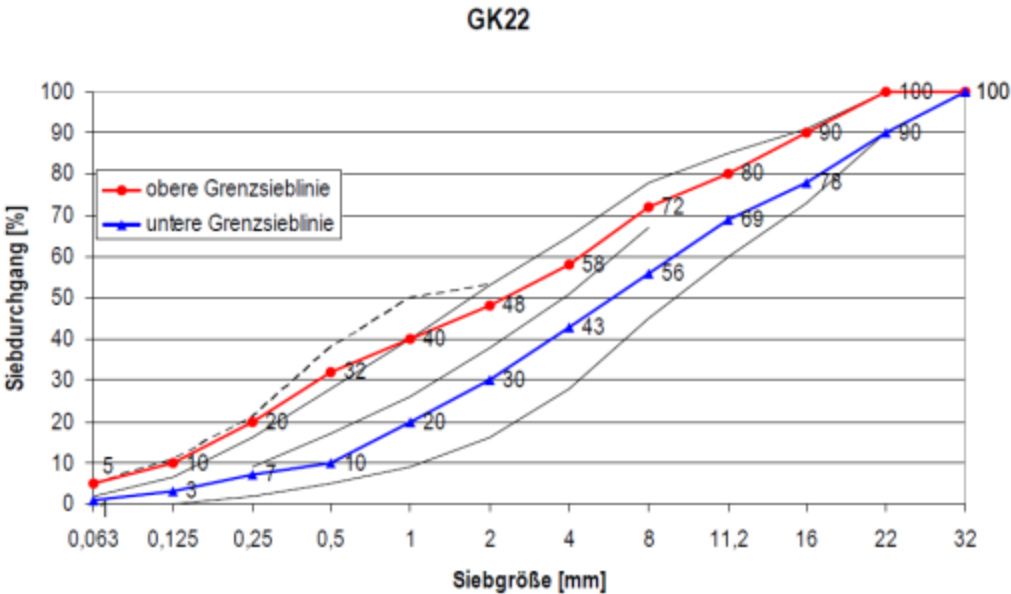**FIGURE 4.2** – Sieve curve model established according to Dreux, Festa (1998)

FIGURE 4.3 : Recommended sieve curve, red : upper limit, blue : lower limit acc. to Merkblatt Weiche Betone, (2009), the Austrian Guideline for Soft Concrete (Siebdurchgang = passing ; Siebgröße = sieve size)

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

- The shape of the aggregate: (naturally) round shape support 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.

While the beneficial effect of modern admixtures in the production of advanced concrete is recognised, the possible negative effect of admixtures should be understood (also part of the current research work). Reducing the quantity of water, by using water reducing admixtures, could in turn increase the viscosity. More paste might be needed to compensate reduced workability. But, 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. In addition, some combinations of cements and admixtures can cause a lack of robustness in fresh concrete, which could lead to excessive segregation (Aitcin, Flatt, 2015).

4.4 Proportioning and production

Mix limiting values should comply with EN 206:2013 and with Annex D in particular where requirements of EN 1536:2010 or EN 1538:2010 have merged, or with the relevant local Standards.

Due to new developments or specific work conditions deviation from these standards might 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 acknowledgement of equivalent performance. These are:-

1) the k-value concept,
2) equivalent concrete performance concept,
3) the equivalent performance of combinations concept.

Appendix C contains details of these concepts.

Following initial development in the laboratory the mix should be trial tested and fine-tuned by full size field batches.

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, 2010).

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 (CIA Z17, 2012). 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 to request detailed batch records with actual mixing time and quantities per truck load.

The process required to produce robust concrete mixes meeting the varied requirements of the specification for fresh and hardened properties is complex and requires careful consideration of each of its constituents and their effect on rheology. Testing for the characterisation of rheological properties is considered in *Section 5*.

The typical steps to develop 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. With regards to detailing (clear distances 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 for economical reason.
4. Selecting the water/binder ratio, based on mechanical and durability requirements.
5. Selecting the necessary workability, based on the method of concrete placement.
6. Estimating the necessary mixing water quantity, based on workability, maximum grain size and shape of aggregate, air content (if required), and use of water reducing admixture.
7. Computing 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 gradings, based on sand fineness.
9. Evaluating the type and amount of admixture to be added, to regulate the concrete workability life, 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.

5 Production and Testing of Concrete, including Acceptance Criteria

5.1 A New Approach to Specifying Fresh Concrete

It is critical that the rheological properties of the tremie concrete are specified for reasons described in *Section 3* and that conformity testing is implemented 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 fully describe the required fresh properties for tremie concrete, particularly in terms of cohesion, flow and flow retention.

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

5.2 Suitability, Conformity and Acceptance Testing

Whilst the suitability testing should involve a wide range of tests, it is up to the specifier to confirm the rheological properties and the tests to be used by the supplier to demonstrate conformity, and for acceptance on site, see figure 1.1. These requirements and tests will depend upon many factors including the complexity of the foundation works.

Recommended acceptance criteria are contained in *Table B1* in *Appendix B.* These should be considered as preliminary and will be amended and finalised at a later date based on the results of the current Research and Development program.

Table B2 in *Appendix B* presents a typical test schedule and makes recommendations on suitable testing regimes.

5.3 The Influence of Time

It is important that the Contractor makes a realistic assessment of the period over which the required properties must be maintained, especially for large pours (> 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:-

- Period required to pour the pile/panel
- Transport distance/time from plant to site
- Concrete plant capacity
- Availability of approved backup facilities
- Truck capacity and number of trucks
- Quality of site access
- Climatic conditions, in particular temperature

A detailed consideration of the above factors will often result in the requirement to extend the workability life (or flow/slump retention, sometimes also referred to as open life) using retarding or workability retaining admixtures, as illustrated in *Figure 5*.

FIGURE 5 - extension of workability time
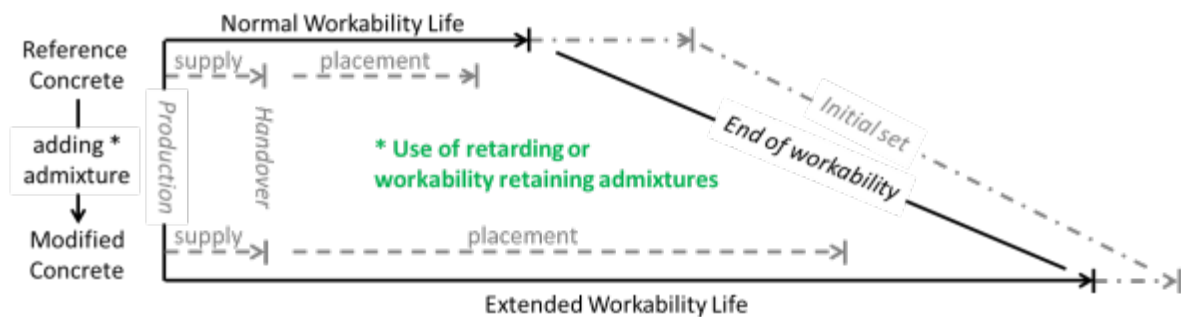
5.4 Quality control on the concrete manufacturing process

Suppliers for ready-mixed concrete should work in accordance with relevant standards and their own quality protocols. The ready-mixed concrete producer shall have product conformity certification with the following minimum requirements:

a) approval of a concrete producer's quality management system, e.g. to EN ISO 9001;
b) product testing by or calibrated against a laboratory accredited for the tests undertaken;
c) surveillance that includes checking the validity of the producer's declarations of conformity, by a certification body accreditation.

Note 1: Conformity control shall be in accordance with the conformity control requirements for designed concretes specified in EN 206:2013, Clause 8.

Note 2: Provisions for assessment, surveillance and certification of production control by an accredited body are as given in EN 206:2013, Annex C.

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 practise to be familiar with the suppliers design, manufacturing and quality control process, prior to ordering concrete. When 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 producers of ready-mixed concrete with the required level of product conformity certification cannot be available it may be possible to use a producer with a lower level of quality assurance. It may then be the responsibility of the customer to ensure the correct quality and consistency of concrete supplied. As a minimum, suitably experienced personnel should check or assess the following items:

• Check calibration of weigh sensors to ensure correct mix proportions.

• Check calibration of flow meters where used for the addition of water etc.

• Check method of measurement of admixtures.

• Check calibration of moisture probes both, automatic where used to measure moisture contents in for example the fine aggregate, and hand held devices used to measure moisture content in the stock piles.

Generally, the following are considered good practice in order to supply tremie concrete with consistently suitable quality:-

- 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. As a minimum the moisture contents should be checked twice a day.

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

- Controls 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. These are not precise measurements and measurement of actual water content should be 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. ASTM C1602 (2012).

  Note 1: The use of re-cycled water might require additional admixtures to ensure desired workability. Workability retention should be retested if using re-cycled water.

  Note 2: Presently, some contractors are reluctant to accept re-cycled 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 mixing time should be checked weekly.

- 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.

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

  Note: The ready-mixed concrete producer should be required to declare for approval any waste minimization system that involves the retention and re-use of 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 and diaphragm walls).

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

This Section does not cover "dry" pouring conditions where the concrete is usually allowed to free fall over a certain height. EN 1536:2010 allows 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 75mm [3 in] of water on the base of the bore, and an inflow not greater than 25mm [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 into 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. 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. 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 chapter 19 of [FHWA GEC10, 2010].

It should be noted that the geometry of the excavation tool will dictate the shape of the base. With diaphragm wall grabs, a curved profile is formed at the base of each bite. In such cases it is essential that the location of any base cleanliness checks are carefully considered and recorded. Figure 6.1 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 center bites.

Bases of piles are cleaned using a cleaning bucket or other approved system. Bases of diaphragm walls are normally cleaned using the excavation equipment or other approved system.

Special tools can be used to remove excessive filter cake from the faces of the excavation (built up during the excavation stage) or the faces of adjacent elements (built up due to the interaction between fresh concrete and bentonite). This is not a standard procedure and is in most cases not required, but can be considered due to design requirements, time of exposure or based on special requirements. In general, the excavation tool with the nominal cross section is normally sufficient to remove any excess cake.

The support fluid should be clean prior to insertion of the reinforcement cage. A sample of support fluid should be taken from the base of the excavation.

The properties of a bentonite sample should be as shown in *Table 6.1.*

TABLE 6.1 - compliance values for bentonite support fluid prior to concreting [EN 1538:2010, FHWA:2010]

Property	Test Method	Compliance Value
Density	Mud Balance	< 1.150 g/ ml (72 lb/ft³)
Viscosity	Marsh Cone	≤ 50 seconds
Sand Content	Sand Screen Set	< 4 %

If polymers are used as the support fluid the values given above will require modification (EN 1536:2010, clause 6.2.2, FHWA GEC10, 2010, clause 7.4.4). FHWA recommends the properties shown in *Table 6.2*.

**TABLE 6.2** - compliance values for polymer support fluid [FHWA GEC, 2010]

Property	Test Method	Compliance Value
Density	Mud Balance	≤ 1.025 g/ ml (64 lb/ft³)
Viscosity	Marsh Cone	≤ 135 seconds
Sand Content	Sand Screen Set	< 1 %

More stringent compliance values might be needed in certain specific conditions such as long pours to minimize the risk of debris settlement.

Before commencement of pouring, it should be confirmed that the actual pre-pouring conditions are in accordance with 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 extreme cases such as multi bite panels founded on hard rock. Where the panel is stepped, the placement process must take this into account.

FIGURE 6.1 – base line reflecting the excavation tool geometry (example using a cutter)
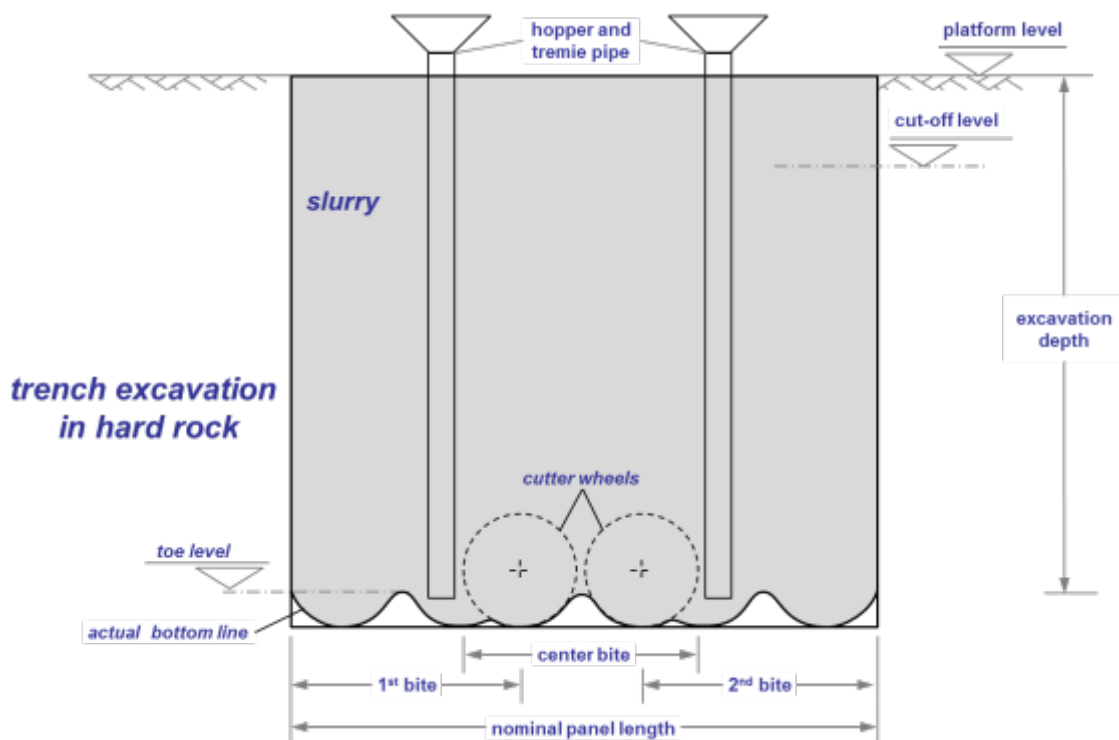
The time elapsing between the final cleaning of the excavation and commencement of concreting shall be kept as short as possible. Where elements such as stop ends or reinforcement cages are to be inserted, cleaning should be carried out before insertion. The cleaning procedure, as well as the time between 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. 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 Pipe and Hopper

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 1536:2010). A diameter of 250 mm [10 in] is commonly used. Closed tremie systems (pump lines) may be smaller than 150 mm [6 in].

Tremie pipes should be made from steel, as aluminium reacts with concrete. Plastic tremie pipes are not common but may be used as long as they are sufficiently robust.

Segmental pipes should be connected by a fully watertight structural connection. Typical sections have a length of 1 to 5 m [3 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). They should be split at every joint each time they are used to avoid laying long lengths of pipe horizontally on the ground, and to allow proper cleaning. There have been examples of joints breaking during tremie handling, so that 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 a sufficient volume to allow for a continuous concrete supply to the tremie. 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 to 2.5 m, maximum 3 m [6 to 10 ft] (SPERW, 2007, EN 1538:2010, CIA Z17, 2012). It is recommended to limit the distance 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.

The tremie pipes should be positioned as symmetrically as possible in plan to avoid uneven rises in concrete level, i.e. 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 placement methods are quoted in Standards and Papers [FHWA GEC10].

In the dry initial placement method, 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 100 mm to 200 mm [6 to 12 in] to allow the concrete to flow into the excavation.

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 shall 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.

Figure 6.2 shows the pressure conditions before and during the stages of the pour. It highlights the fact that before the first cut the tremie pipe must be sufficiently embedded. The required concrete level should be assessed for each specific site condition but in most circumstances a minimum of 5 m [15 ft] is required before the first split of the tremie. It is essential that a sufficient volume of concrete is available on site before the pour is commenced.

FIGURE 6.2 - phases in the tremie pour sequence
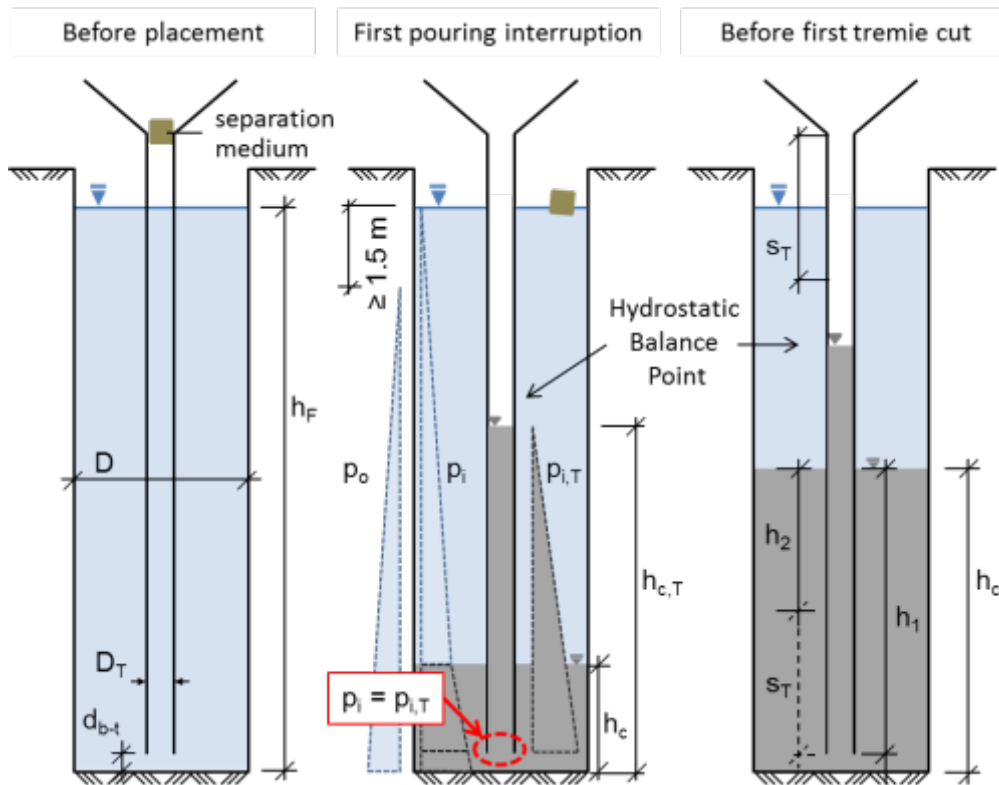
Where:

h_F	Fluid level in excavation
D_T	Diameter of tremie pipe
D	Dimension (diameter or thickness) of excavation
d_{b-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 of tremie pipe

6.6 Tremie Embedment

The tremie requires a minimum embedment into the concrete that has already been poured. Execution Standards (EN 1536:2010, EN 1538:2010) specify a minimum embedment of 1.5 to 3 m [5 to 10 ft], with higher values for larger excavations. In general a minimum embedment of 3 m is well accepted in practice. 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].

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 2 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 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 6.2. 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.

Excessive tremie embedment can lead to excessive resistance to flow, which might, for example, then cause lifting of the reinforcement cage in the early stages of the pour.

There are strong technical arguments to avoid excessive tremie embedment. Greater embedment leads to lower head pressure, loss of energy supply and leads to slower concrete flow. The ICE Specification for Piling and Embedded Retaining Walls limits the maximum embedment to 6 m [20 ft] (SPERW, 2007). Experience from the industry suggests it is good practice to use embedment between 3 m [10 ft] minimum and 8 m [25 ft] maximum. For bored piles with a diameter of 750 mm [30 in] or less the maximum embedment may be increased to 12 m [40 ft].

It is good practice to measure the depth to the concrete at tremie positions after each load of concrete has been placed. It can also be helpful to determine the hydrostatic balance point by measuring the depth to the concrete within the tremie pipe.

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 might 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 should be agreed in advance.

6.7 Concrete Flow Patterns

Concrete flow patterns are not well understood. Further research is ongoing, where the concrete flow patterns from the tremie pipe are numerically modelled using fluid dynamics programs or simulations [Böhle, Pulsfort, 2014]. *Figure 6.3* 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.

Further research, funded by the Sponsors of this Guide, is being carried out by the Technical University of Munich, to allow greater understanding of the critical rheological parameters of fresh concrete which can affect the flow.

FIGURE 6.3 – Cross section of a bored pile cast with differently dyed loads of tremie concrete

6.8   Flow Around Reinforcement and Box-Outs

As set out in Chapter 2, special considerations have 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 higher travel distances from the tremie pipe outlet and at higher elevations where the concrete head pressure is lower.

The recommendation must be a combined consideration of concrete rheology, placement method, and detailing in the design, including a sufficient allowance for over-pouring above the cut-off level.

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 should be measured and the embedded length of the tremie pipe recorded at regular intervals corresponding to each load of concrete.

The depths measured, volumes placed and tremie lengths should be plotted immediately on a graph during the pouring operation and compared with the theoretical values. An example of such a graph is given in Annex C of EN 1538:2010.

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 critical information on any deep foundation element is to install one or more full scale test elements and 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

and they should follow regional execution standards.

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 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

Bored piles and diaphragm walls are cast against a soil face and the casting process is not visible from the surface. Some imperfections are inevitable within an industrial production environment. Quality control of the completed works should therefore make allowance for acceptance of some imperfections where these are not significant with regard to the structural strength and durability of the completed 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 when it is in many ways too late. It can also be possible 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 corrective action 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 used methods is contained in *Appendix D.*

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 (maybe also referred to as Shadowing or Quilting)

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

Imperfections can be caused by concrete which 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 contained within this Guide should reduce the imperfections to an absolute minimum.

APPENDIX A – TEST METHODS TO CHARACTERISE FRESH CONCRETE

a) **Rheology**

Concrete, in terms of its grain size distribution, is not homogeneous. Therefore, its rheology cannot be determined accurately with absolute physical parameters, namely yield stress and plastic viscosity. Instead, each rheometer –an apparatus measuring rheological parameters– includes a specific variable that cannot be calibrated as there is no direct relationship. An example of a principal test set-up is shown in the figure below.

By employing the same test set-up on a significant sample of concretes a fundamental understanding can be derived by comparison of different concretes at different stages, which is part of the research program presently undertaken on behalf of EFFC and DFI.
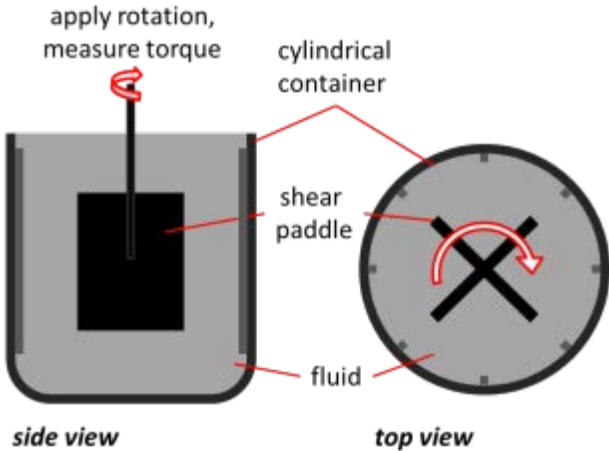
Note: The rheometer is generally considered as a laboratory testing device.

b) **Workability**

The test methods described below all have in common, that they cannot separate viscosity or yield stress from the actual concrete's rheological behaviour. However, the great advantage of the following tests is their practicability which, together with their proven repeatability accuracy, makes them acknowledged international standard tests.

b1- Flow table test acc. to EN 12350-5

Principle: The spread of the concrete is a measure of the consistence.

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 and the initial slump the plate is lifted and dropped 15 times which leads to the final spread.

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

b2- Slump test acc. to EN 12350-2, ASTM C143

Principle: The slump of the concrete results in a measure of the consistence.

Procedure: The fresh concrete is filled and compacted in a mould which consists of a 30 cm [12 in] high hollow truncated cone. With raising the cone the concrete will slump.

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

b3- Slump Flow test acc. to EN 12350-8, ASTM C1611

Principle: The slump flow is a measure of the consistence and, in part, of the flowability.

Procedure: The fresh concrete is filled in a form which consists of a 30 cm [12 in] high hollow truncated cone. With raising the cone the concrete will slump and flow. The final diameter of the concrete is measured (slump flow in mm). The test can also be extended to measure the time taken for the concrete to spread.

Remarks: A serious lack of stability can potentially be detected visually, see d3. The original test specifies T_{500} as the time the concrete needs to spread to a diameter of 500 mm [20 in]. Since common tremie concrete might not necessarily spread that far, at least not far above 500 mm [20 in], T_{final} can be defined alternatively as the time the concrete need to reach final spread, i.e. final diameter D_{final}, see figure below [CIA Z17, 2012].
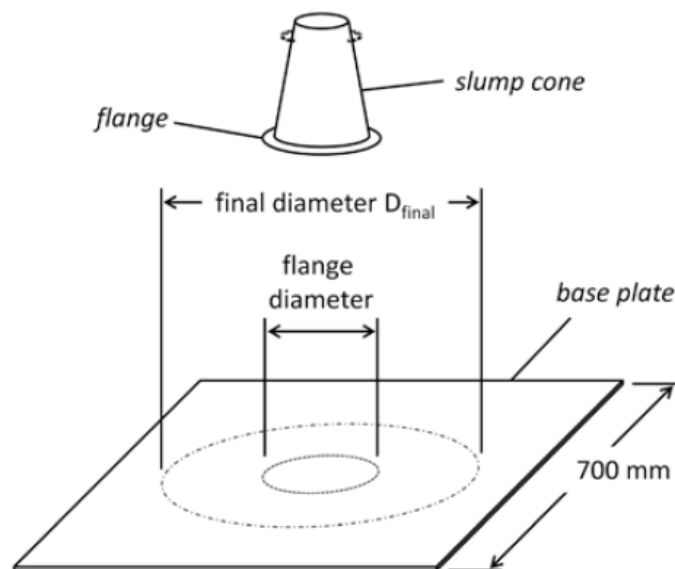
### b4- L-Box test acc. to EN 12350-10, and Australian Tremie Handbook (ACI Z17)

Principle: The test is used to assess the workability in conjunction with passing ability.

Procedure: The gate is closed and the vertical section of the apparatus is filled and compacted with concrete. After 1 minute the sliding gate is opened, and the

concrete starts flowing through the gate with (2 or 3) smooth bars simulating reinforcement obstructions.

Within standard testing the heights within the vertical section H1 and at the end of the horizontal section H2 are measured and H2/H1 will be recorded as measure of both workability and blocking resistance. Instead of using the ratio H2/H1, the Tremie Handbook recommends to record only the absolute height f_{end} at the end of the box, to the nearest 5 mm. For concrete which does not reach the end of the box the travel distance from the gate should be recorded instead of the filling height.

Within the extended test, the time is measured which the concrete needs to pass defined travel distances of 200 and 400 mm [8 and 16 in]. The Australian Tremie Handbook recommends measuring the time for reaching the far end of the horizontal box and record the arrival time T_{end}, as a measure for flowability.

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

It is recommended to use only 2 bars unless the maximum grain size is 10 mm [4 in] or below where 3 bars should be used.
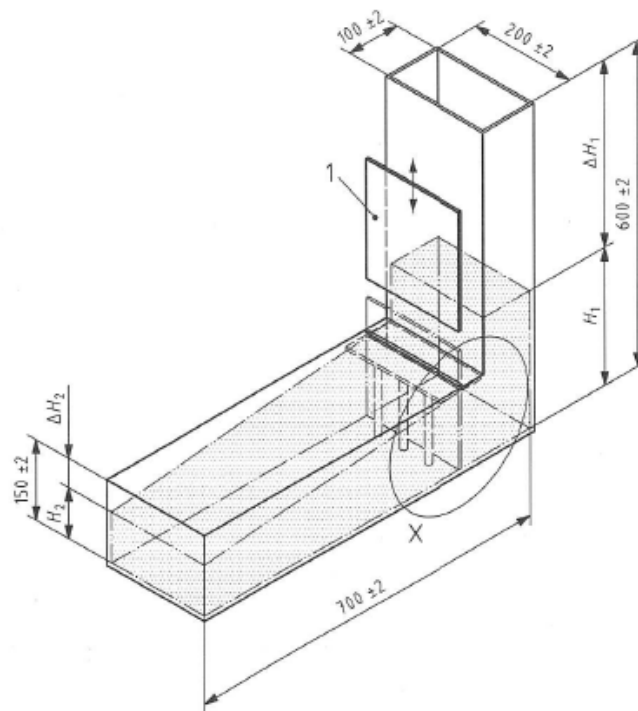
c) Workability Retention (Workability Time):

The workability retention or workability time is referring to a generic term indicating the total time span required to have concrete of sufficient workability at all times during discharge and placement to fill gaps. The end of workability time happens significantly before setting acc. to EN 196-3 which is meant for cement paste.

c1- slump retention test

Principle: Observe workability over scheduled pour time, by use of slump test (b2).

Procedure: Batch at least 3 m³ [4 yd³] fresh concrete and store in ambient conditions. Prevent from draining or drying over test duration by lining/covering or storing into form. Perform slump tests every 2 hours by using a fresh sample each time.

Slump >180 mm [7 in] and/or slump flow >400 mm [16 in] are recommended values for good workability of tremie concrete at the end of scheduled pour time.

Remarks: In principle, the flow table test could be used accordingly. Recommended values have not been identified.

c2- knead bag test

Principle: Detect the change of consistence, resulting from hydration.

Procedure: About two litres of fresh concrete are filled in a plastic bag. By placing the knead bag on a flat hand and press a thumb into the fresh concrete at regular intervals, the actual stage of consistence in accordance with the following table is detected and to be recorded.
The Australian Tremie Handbook considers a transition from liquid to soft consistence as noticeable stiffening and therefore as critical time for placement under wet conditions.

Remarks: The later transition from soft to plastic consistence may already indicate the commencement of setting. Again only qualitatively, the initial set and final set might be detected, see below table (CIA Z17, 2012).

Consistency	Behaviour at kneading	Hydration phase
Liquid	Running around flat hand	-
Soft	Slumping on flat hand, easily deforming when pressed	-
Plastic	No movement around flat hand, kneadable	Initial set
Stiff	Compressible, but less than 30 mm	
Semi-firm	Compressible, but less than 10 mm	-
Firm	Compressible, but less than 1 mm	Final set

c3- Stiffening time index test

Principle: The test can be used to determine the time span of stiffening of a flowable or soft concrete by repeatedly testing the concrete's ability to close a hole by effect of its self-weight.

Procedure: Fill several containers (buckets) with fresh concrete from the load to be investigated. Seal the containers so that no water can evaporate from the surface of the concrete sample, and avoid direct sun radiation or other impacts on the concrete samples.
At pre-defined time intervals, which should be based on the planned pouring or workability time, push a stick or reinforcement bar (of dia 40 to 50 mm [1.5 to 2 in]) into the fresh concrete by at least 15 cm [6 in] and immediately but slowly extract again.
The particular concrete sample can be assessed as still not stiffened resp. as still in its fresh stage until the gap closes again - without leaving a hole deeper than the bar diameter used. The time span of transition in its ability to close the gap properly should be recorded as stiffening time span.

d) **Stability:**

The stability, namely the resistance to segregation, bleeding, and filtration might be quantified by the following tests.

d1- Visual Stability Index Test (VSI) acc. to ASTM C1611

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

Procedure: Same as with slump flow, followed by visual inspection using criteria listed in the table below

Remarks: The Australian Tremie Handbook(CIA Z17, 2012) recommends allowing VSI value 0 only.

| 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 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 center of the concrete mass.

d2- Static Segregation or Washout test following ASTM C1610 or 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 (original standard and guideline allow no compaction or vibration, for SCC mixes). After a standard period, e.g. of 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. However, limited experience for this test exists for use of Tremie concrete.
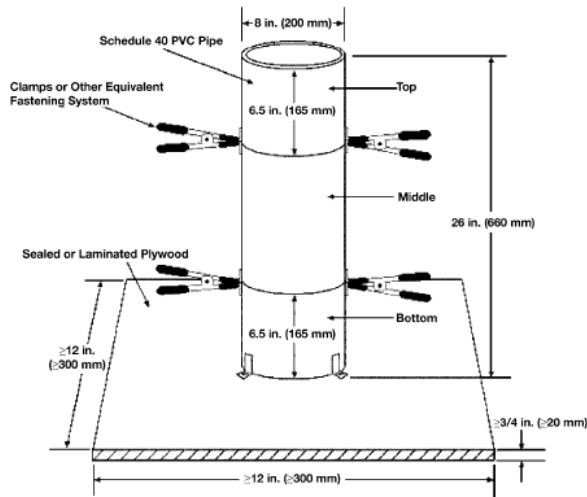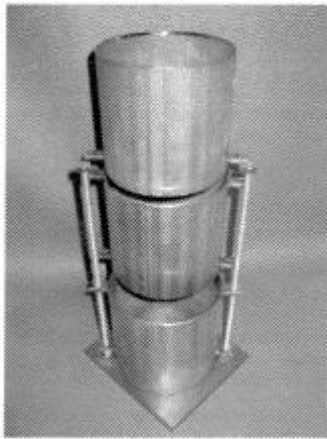
d3- Hardened Visual Stability Index (HVSI) test acc. to AASHTO PP58-12

Principle: The test evaluates static segregation by examination of aggregate distribution in a hardened test specimen sawn in two.

Procedure: A standard cylinder mould is filled with concrete, without compaction or vibration, and allowed to harden undisturbed. Once strong enough the specimen is sawn in two, axially, and the aggregate distribution compared with standard descriptions and photographs to determine the HVSI class.

Remarks: The test was developed for self-compacting concrete but is likely to be equally applicable to tremie concrete. It has the advantages of taking the full setting time into account, and not needing specialist equipment other than a concrete saw. It does, however, take several days for the concrete specimen to be strong enough to saw;

d4- Bleeding test acc. to EN480-4, ASTM C232

Principle: The amount of water on the surface of concrete in a container is a measure for bleeding.

Procedure: Concrete is inserted into a cylindrical container. The segregation of water at the surface is measured until the bleeding stops resp. setting of the concrete.

Remarks: Some contractors rely on the significance of this test and look for an average bleeding rate after 2 hours of less than 0.1 ml/min.
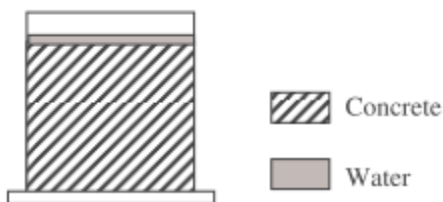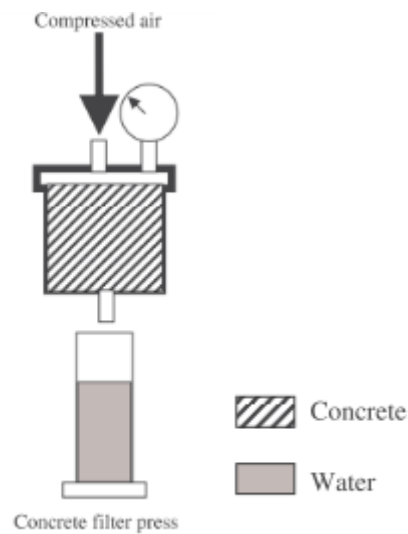

d5- Concrete Filter Press test acc. to Guideline on Soft Concrete (Merkblatt Weiche Betone, 2009)

Principle: The test simulates the water retention ability of fresh concrete under hydrostatic pressure and determines the filter loss through a filter.

Procedure: A cylindrical container is filled with 10 l [2.5 GAL] of fresh concrete and pressurized with compressed air (3 bar [44 psi]). The water which separates from bulk concrete through a filter paper is collected at the bottom of the container in a cylinder. The recorded filter loss is a measure for the filtration stability of the concrete.

Remarks: The stability class FW20 is defined for tremie concrete (where depth exceeds 15 m [50 ft]). The acceptance criterion of maximum 20 l/m³ [4 GAL/cy] is recommended for suitability testing and 15 minutes filtration time. The according test value for the 10-l sample is 200 ml [6.8 oz].
Industry internal tests indicate an acceptable correlation between the concrete filter press test acc. to ÖVBB Richtlinie and the BAUER filtration test which is
$V_{loss-15,ÖVBB} / V_{loss,BAUER} = 1.8$ (approx. 2)

Concrete filter press

d6- Bauer filtration test acc. to Australian Tremie Handbook (ACI Z17, 2012):

Principle: The test simulates the water retention ability of fresh concrete under hydrostatic pressure and determines the filter loss through a filter.

Procedure: A cylindrical container is filled with 1.5 l [0.4 GAL] of fresh concrete and pressurized with compressed air (5 bar [73 psi]). The water which separates from bulk concrete through a filter paper is collected at the bottom of the container in a cylinder. The recorded filter loss is a measure for filter stability of the concrete. The also measured filter cake thickness is an additional measure for the concrete's robustness against loss of workability.

Remarks: The Australian Tremie Handbook limits the maximum aggregate size to 20 mm. The same guideline recommends an acceptance criterion of 15 l/m³, for tremie concrete in deep foundations (>15 m [50 ft] depth). The according test value for the 1.5-liter [0.4 GAL] sample is approx. 22 ml [0.7 oz].
Industry internal tests indicate an acceptable correlation between the 'Austrian' concrete filter press test (d5) and the BAUER filtration test which is
$V_{loss-15,ÖVBB}$ [l/m³] / $V_{loss,BAUER}$ [l/m³] = 1.8 (approx. 2)

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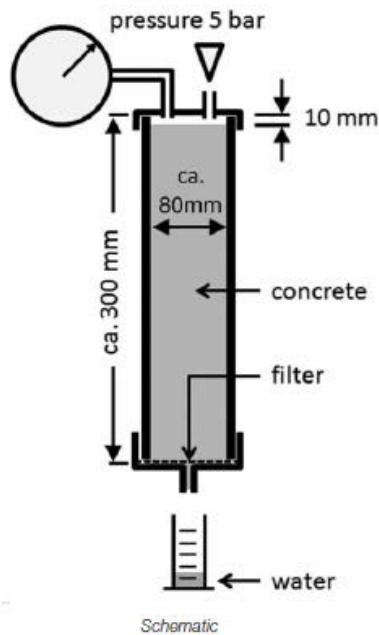
Note: The test equipment is based upon the standard testing for drilling fluids acc. to API RP 13B-1, also referred to in EN ISO 10414-1

e) Composition of fresh concrete

In order to identify the actual composition in compliance with the designed, indicators like density, water content, water/cement ratio, content of fines < 0.125 mm [125 mesh], content or shape of coarse aggregates might be specifically tested, by a specialized laboratory.

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

APPENDIX B – INITIAL RECOMMENDATIONS ON ACCEPTANCE CRITERIA FOR SELECTED TEST METHODS

Note: *Table B1* is preliminary and will be reviewed on base of the current R&D project, see chapter 1.2.

TABLE B1 – possible acceptance criteria for Tremie Concrete to be applied in deep foundations.

	Test Method and Concrete Properties	Recommended values – *under review* *
1	Combined Slump, Slump Flow and VSI test	
	Slump	$h \geq 180$ mm [7 in] *minimum stability to be controlled by testing of VSI*
	Slump Flow	400 mm [16 in] $\leq D \leq$ 600 mm [24 in]
	Time to reach final spread	3 s $\leq T_{final} \leq 11$ s
	Visual Stability Index (VSI)	0
2	L-Box test	
	Time to reach end of box	$T_{end} \leq 12$ s
	Filling Height at far end	$f_{end} > 0$ mm
	Blocking of bars	No
3	Filtration test *(for application in depths > 15 m)*	
	Filtration Loss (*15 l/m³ in BAUER f*iltration test corresponds with ca.:)	$V_{loss,A} \leq 270$ ml [9.1 oz] (AUSTRIAN filtration test) $V_{loss,B} \leq 22$ ml [0.7 oz] (BAUER filtration test)
	Filter Cake Thickness	$h_{cake,B} \leq 100$ mm [4 in] (BAUER filtration test)
4	Bleed rate	$x_{bleed} \leq ...$ (value to be specified on project basis)

* the above mentioned values are taken from the Australian Tremie Handbook (ACI Z17, 2012).

TABLE B2 – test types and typical test schedule

Test Method	Determines					Application / Test Frequency for	
	Consistence	Flowing Ability	Passing Ability	Segregation Resistance	Water Retention	Conformity -in lab-	Acceptance -on site-
Flow Table / Slump	✔					M	Each load*
Slump Flow	✔	(✔)**				R	Each load*
VSI				✔	✔	R	Each load*
L-Box		✔	✔	(✔)***		R	On demand
Filtration				(✔)****	✔	R	On demand
Segregation				✔		P	-
Bleeding					✔	R	On demand
slump retention	✔ over time					R	On demand

M = Mandatory; R = Recommended; P = Possible
* Testing frequency might be reduced as per project specifications once target values have been reliably achieved
** If measured, the time the concrete needs to reach a certain spread can be an indication for flowability
*** Extra information on stability can be gained if the test is executed after a certain resting time (e.g. 60 min)
**** Often, a concrete with higher filtration resistance will have a higher segregation resistance

APPENDIX C – Use of Additions Concepts

Specified minimum cement contents for concrete in bored piles and diaphragm walls 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). These are:

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 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 206:2013.

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 206:2013.

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 for which 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, 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 EN 197-1 and addition (or additions) having established suitability that may count fully towards requirements for maximum water to 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 equivalence 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 D – 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 standard and industry best practice. However, post-construction testing has 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 App F.

Both, destructive and non-destructive testing methods generally 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, only cross-hole sonic logging (CSL) and thermal integrity profiling (TIP) are described representing the non-destructive testing methods. 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 described, e.g. in Recommendations on Piling (2012) or FHWA GEC (2010), or in expert literature for non-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 transmitter 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.

Thermal Integrity Profiling

Thermal integrity profiling (TIP) is a developing technology.

It uses the heat of hydration of the concrete and the differences in thermal conductivity between inclusions and soil one or two days after pouring to produce a variation in temperature near the edge of the element. The test method is detailed in ASTM D7949-14.

The temperatures are monitored by strings of thermistors attached to the reinforcement cage. Optionally, thermal probes are used guided in tubes within the foundation element.

In most applications, lack of increase in temperature indicates a locally lower cement content compared to the pile's average and this is interpreted as a thermal anomaly (potential defect). The locations of the wires are in an array within the reinforcing cage of the foundation. The wire arrays allow for thermal data to be acquired throughout the shaft, allowing for a full 3 dimensional analysis of the shaft. The system can evaluate both the core of the shaft as well as the cover zone and can also give information on reinforcing cage alignment.

APPENDIX E – INTERPRETATION OF IMPERFECTIONS

Imperfections within a deep foundation element, which as per definition deviate from the expected (sound) quality and/or regular continuity of the cast in-situ reinforced 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 which may lead to a deficiency of the deep foundation element. For example, marks in the concrete surface of piles from withdrawn excavation tools are inevitable, see figure E.1. Such grooves should not be considered as imperfections, as long as they do not compromise the structurally required minimum cover after execution.

Figure E.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.

Anomalies' formation mechanism
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 o.k.?

- Insufficient workability time – retarder dosage according to flow retention specified?

- Instability of concrete – Presence of a thick interface layer of material rising atop 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.

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:-

1) 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, or poorly cemented material originated from segregated concrete. Two examples are shown in *Figure E.2*.

Figure E.2: Severe 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 D. These tests need special knowledge and experience with which the imperfection's extent might be assessed by further evaluations.

2) Channelling

Channelling is also referred to as bleed channels. These are vertical narrow zones with lightly cemented aggregate respectively 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 E.3*. In addition, bleed water can pass up around vertical installations within the cross-sections e.g. longitudinal reinforcement bars, or within the core of wide elements.

Figure E.3: Severe examples of channels running up the surface of a pile and a diaphragm wall

3) 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 shadow of 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 possible defect, and investigated further, see figures E.4 and E.5.

The formation of mattressing is associated with a horizontal flow of concrete through reinforcement into the cover zone 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 E.4: Shadowing in a pile (left); mattressing in a panel (right)

Figure E.5: Schematic showing varying degrees of mattressing
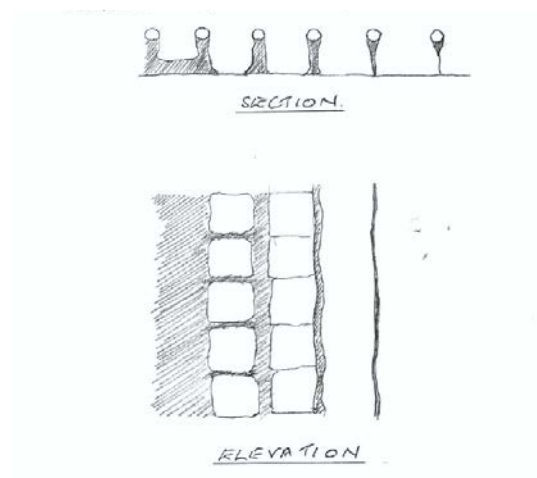
APPENDIX F – Detailed information on Design Considerations

This Appendix should be read in conjunction with Section 2 and includes supplementary information on detailing, concrete cover, single columns on single piles, and end bearing capacity, all related to the impact of the 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. The clear spacing requirements should not be broken in any circumstance. 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)
- 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.

In particular, the bar spacing affects the ability of concrete to flow in the cover zone. 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. Detailing requirements for cages are summarized in *Table F.1, F.2 and F.3*.

Transverse reinforcement which runs through the centre of the reinforcing cage, (couplers, links, tie rods) affects the vertical upward flow of the concrete.

TABLE F.1 – *Commonly used reinforcement requirements for Bored Piles*

Minimum reinforcement for __Bored Piles__			
Location	Clause	Value	Comment
Vertical	ACI336.3R, 3.3 referring to ACI318,10.9.1	1% A_C	for elements in compression that cannot be designed as plain concrete, where A_C is nominal cross section (where this is larger than required for structural reasons, ACI318, 10.8.4 permits A_C to be taken as a reduced area for both strength and minimum reinforcement, but not less than half the nominal cross section,)
	EN1536, Table 5	0.5% A_C $0.0025m^2$ 0.25% A_C	$A_C \leq 0.5m^2$ where A_C is nominal bored pile cross $0.5m^2 < A_C \leq 1.0m^2$ section. $A_C > 1.0m^2$
Horizontal	ACI336.3R, 3.3 referring to ACI318,10.9.3		expression (10-5) gives minimum area of spiral reinforcement.
	EN1536, Table 6	≥ 6mm ≥ one quarter of the maximum diameter of the longitudinal bars ≥ 5mm	Links, hoops or spiral reinforcement. wires of welded mesh transverse reinforcement.
Spacing for __Bored Piles__			
Location	Clause	Value	Comment
horizontal and vertical spacing of bars	ACI336.1, 3.4.9	≥ 100mm ≥ $4D_G$	including at laps. where D_G = maximum aggregate size, including at laps.
	EN1536, 7.5.2.5 EN1536, 6.3.2.2 EN1536, 7.5.2.6 EN1536, 7.5.2.7 EN1536, 7.5.2.9	≤ 400mm ≥ $4D_G$ ≥ 100mm ≥ 80mm ≥ $1.5D_G$ and ≥ $2.0D_S$	 where D_G = maximum aggregate size. for single or bundles of longitudinal bars. for lap length, provided that $D_G \leq 20mm$ (special consideration must be given to the maintenance of sufficient concrete flow, see sections 3 and 6). for layers of bars, placed radially, where D_S = (steel) bar diameter.

TABLE F.2 – *Commonly used reinforcement requirements - for Diaphragm Walls*

Minimum reinforcement for __Diaphragm Walls__			
Location	Clause	Value	Comment
Vertical – (Diaphragm walls / unit length	EN1992-1-1, 9.6.2 EN1538, 7.5.3.1 EN1538, 7.5.3.1	0.2% A_C $D_S \geq 12mm$ ≥ 3 bars /m	where A_C is nominal area of panel / unit height. where D_S = (steel) bar diameter.
Horizontal - diaphragm walls / unit height	EN1992-1-1, 9.6.3 EN1992-1-1, 9.6.3 No specific requirements in EN1538	≥ 0.1% A_C ≥ 25% A_{SV}	where A_C is nominal area of vertical section through panel / unit height. where A_{SV} is area of vertical reinforcement.
Spacing for __Diaphragm Walls__			
Location	Clause	Value	Comment
horizontal spacing of vertical bars	EN1538, 7.5.3.3 EN1538, 7.5.3.2 EN1538, 7.5.3.3	≥ $4D_G$ ≥ 100mm ≥ 80mm	where D_G = maximum aggregate size. of single bars or groups, parallel to the wall face. for the lap length or in the case of heavily reinforced panels. (special consideration must be given to the maintenance of sufficient concrete flow, see sections 3 and 6).
vertical spacing of horizontal bars	EN1538, 7.5.4.2 EN1538, 7.5.4.3	≥ 200mm ≥ 150mm	 where required, provided that $D_G \leq 20mm$, where D_G = maximum aggregate size.
horizontal spacing of horizontal bars	EN1538, 7.5.4.4	≥ 150mm	

TABLE F.3 – *common requirements on bond, anchorage, laps and crack width*

Bond, anchorage (development lengths) and laps (splice lengths) for <u>Bored Piles</u> and <u>Diaphragm Walls</u>		
Location	Clause	Comment
Anchorage	ACI318, 12.2	Bars in tension.
	ACI318, 12.3	Bars in compression.
	ACI318, 12.4	Additional rules for bundled bars.
Lap length	ACI318, 12.15	Bars in tension.
	ACI318, 12.16	Bars in compression.
	ACI318, 12.17	Additional rules for columns, which are assumed to apply also to piles.
Bond strength	EN1992-1-1, 8.4.2	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., ref 8) should be sought on the impact on bond of support fluids.
Anchorage length	EN1992-1-1, 8.4.4	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.
Lap length	EN1992-1-1, 8.7.3	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).
Crack widths		
Location	Clause	Comment
Calculation of crack widths	ACI336.3R	No requirements
	EN1992-1-1,7.3.4	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.

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 through the cover and to obtain dense durable concrete in this 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 below.

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

The recommendation of this guide is that the minimum nominal cover for execution should be:-
1) For structures cast against the ground (without preparation) a nominal cover equal to 75 mm [3 in] is proposed, i.e. a minimum cover of 50 mm [2 in] plus a tolerance of 25 mm [1 in]
2) For structures where a casing is used a nominal cover equal to 50 mm [2 in] is proposed, i.e. a minimum cover of 35 mm [1.5 in] plus a tolerance of 15 mm [0.6 in]

For concrete cast directly against the ground, the higher tolerance should cover effects from a possible build-up of filter cake or other adverse effects on the actual cover.

The minimum nominal cover should be increased in cases where the structural minimum cover, e.g. according to EN 1992, is greater than the minimum nominal cover values for execution given above, e.g. due to specific durability requirements in place, by the amount of the difference.

The minimum nominal cover in temporary cased borings should also be increased if the conditions for concrete flow are considered critical, which might be the case for reasons given in Clause 7.7.3 of EN 1536:2010, i.e. for small diameter piles (< 0.6 m [2 ft]), where a large maximum grain size of 32 mm [1 ¼ in] is used, if concrete viscosity is considered increased, e.g. where silica fume partly replaces cement, or in soft soil.

To allow installation of the reinforcement cage into the excavation (or casing) an additional allowance may be considered in the detailing.

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 [CIRIA Guide C580, ACI 350].

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 F*. 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.

FIGURE F – *connection details for a bored pile used to support a super-structural column*
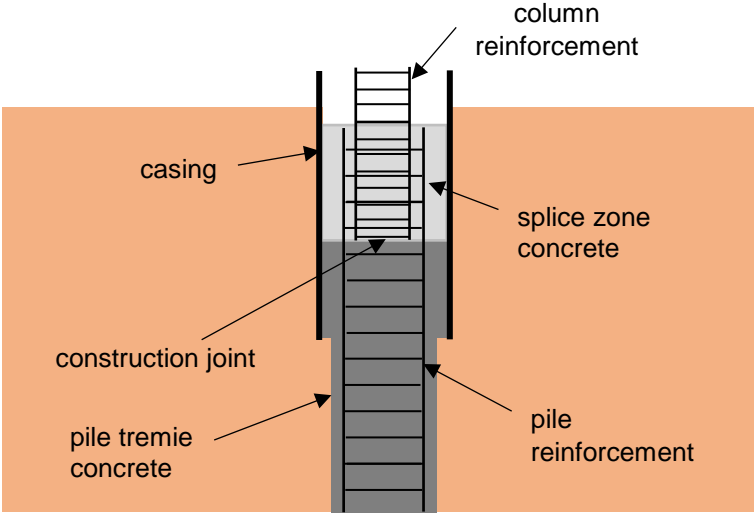
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