New Approach for Tremie Concrete used for Deep Foundations

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Synopsis: Constructing deep foundations usually consists of two distinctive steps: (1) excavation of soil or rock and (2) placement of reinforcement and concrete. This paper describes special testing, design and pouring practice requirements for successful tremie concrete constructions of deep foundations. It is argued that current state of the art practice is inadequate and hence a new guideline must be developed for tremie concrete practice.
Tremie concrete for deep foundations must be of excellent workability and needs to be highly reliable under “blind placement operations” and considerable hydrostatic head pressures. Concrete must flow easily around reinforcement bars and no aggregate segregation or water bleeding shall occur under these extreme conditions. Furthermore, workability and consistency must be maintained for several hours at a constant, continuous level from first to last concrete batch.
Currently the only accepted testing method for tremie concrete workability is the slump cone test. The paper highlights that “slump” alone is not a reliable indicator for good workability and introduces new criteria such as slump flow.
The paper discusses the key test results obtained from more than 44 different tremie mixes, which were tested throughout the research and gives recommendations what is required for a sufficient tremie concrete mix.

Keywords: tremie concrete, deep foundations, workability, slump flow

1. Introduction

The construction of deep foundations includes piles and diaphragm walls for foundations and retaining structures. Depending on ground conditions and load requirements, conventional bored piles can be up to 100m deep. Diaphragm walls with depth up to 50m have been constructed in the past successfully around the globe. Drilling fluids like bentonite or polymers are common to support the excavation of deep foundations. Concrete for deep excavations has different requirements than concrete for superstructures (figure 1).

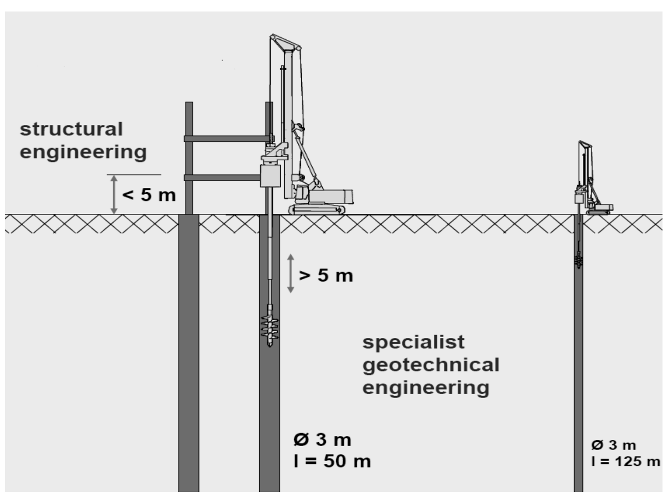

Figure 1. Concrete for deep foundations need different requirements [x]

Concrete for deep foundations must have excellent workability criteria to ensure that it fills the spaces around the reinforcement cage and the soil. Concrete has to displace drilling fluid and form a sufficient bond with reinforcement bars. It is not practical to compact concrete for deep foundations poured under fluid with vibrator, and the concrete must have self compacting and self levelling properties.

Based on the authors' experience, it is not uncommon that placement of concrete for a diaphragm wall panel or bored pile can take 12 hours or longer from start to completion. During this period of time concrete workability criteria must maintain excellent and tolerances in workability are tight. This is particular important for the concrete inside the pile shaft as the fresh concrete rises upwards through the duration of the tremie pour. Experience has shown that the final distribution of concrete depends on the movement of the freshly placed concrete poured into the already placed "older concrete". Besides of the influence of viscosity and gravity of concrete, shape and dimensions of potential obstacles inside the excavation are vital on the actual flow of each concrete batch from start to end.

If the surface of the surrounding soil or temporary steel casing is reasonably smooth and no reinforcement or other obstacles block the upward flow of the concrete inside the excavation, it will remain on the top of the concrete column below, placed beforehand. If a rough surface or in particular a reinforcement cage obstruct free flow upwards, freshly placed concrete batches will tend to flow upwards in the centre of the excavation and push older concrete towards the edge of the excavation. In the latter case each batch will be spread inside the pile or panel similar to the layers of an onion.

However, since there is no evidence about exact concrete flow behaviour inside a pile or panel it must be assumed that the very first batch (followed by consecutive batches) might be pushed all the way up through the reinforcement arrangement. It is obvious that workability criteria must remain unchanged for the entire duration of the pour to ensure an end product without defects. Furthermore, concrete for deep foundations has to maintain its stability throughout the entire placement process to avoid considerable segregation. Concrete placed at the base of the deep foundation element experiences extremely hydraulic and hydrostatic head pressure and it needs to be designed to withstand this pressure. Nevertheless, a minor degree of segregation (bleeding) has to be tolerated otherwise the cut-off level must be significantly below the casting level (figure 2).

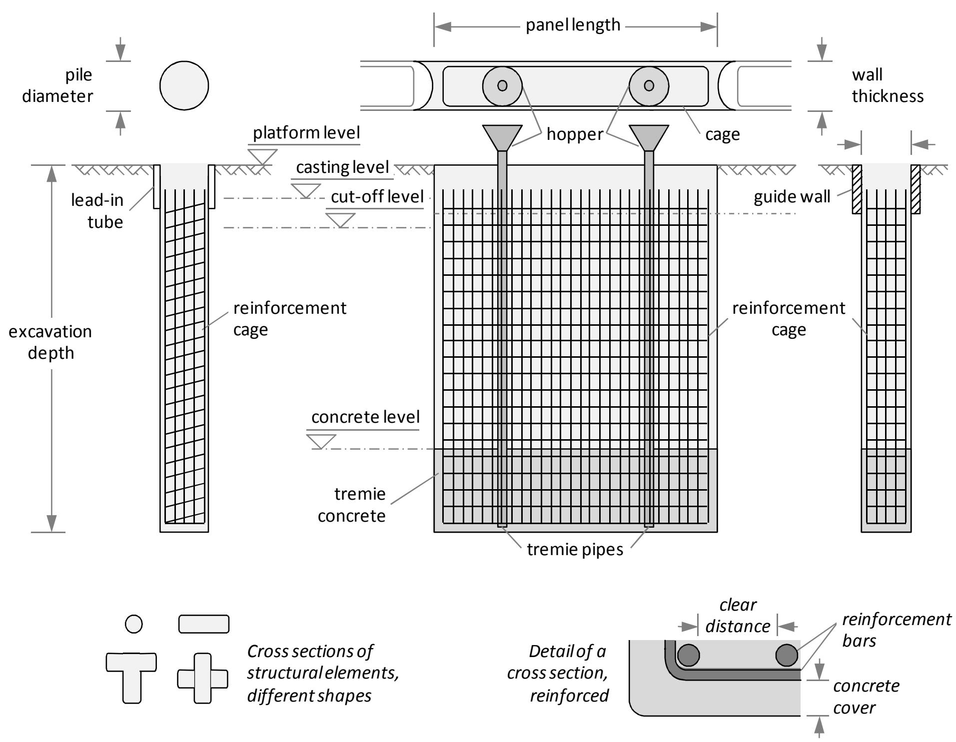

Figure 2. Typical details of deep foundation elements

2. Damages and defects

Every year significant damages on piles and diaphragm walls are caused by the use of insufficient concrete in Australia and the rest of the world. In some cases an insufficient concrete mix is the reason for the damages shown in figure 3, possibly combined with clear distances between reinforcement bars which are too narrow. In other cases a lack of understanding how to install the concrete properly contributes to the problem as well. The piling crew's knowledge how to carry out a tremie pour is as important as the right concrete mix for an end product which is free of damage.

Figure 3 shows typical damages found on piles and diaphragm walls like bleeding channels and honeycombs (lack of stability) as well as insufficient concrete cover, bond with reinforcement and leaks (lack of workability).

Figure 3. Typical damages and defects on piles (left and centre) and diaphragm walls (right) due to insufficient concrete quality.

3. Characteristics of tremie concrete

Main characteristics of Tremie Concrete are its workability and stability, which are defined as follows:

Workability:

Workability describes the ability of the concrete to flow through tight openings such as spaces between steel reinforcing bars without segregation and blocking (passing-ability or blocking resistance). The ease of flow of fresh concrete when unconfined by formwork or any other obstacles such as reinforcement is defined as flowability.

Stability

Stability of tremie concrete mainly consists of the ability of fresh tremie concrete to retain its water despite being subject to pressure caused by supporting fluid or fresh concrete above (water retention) and the ability of fresh tremie concrete to maintain its flow characteristic, measured by slump test, over a certain period of time, possibly controlled by appropriate admixtures (retardation).

It is vital to understand the difference between stability and workability requirements for tremie concrete in comparison to conventional concrete.

Compared to conventional concrete which requires vibration after placement in order to remove trapped air and produce a dense material, tremie concrete has to be self-compacting and thus differs in some composition and workability parameters. It can be argued that tremie concrete can be compared with super-workable concrete because of similar self-compaction requirements which allow the mix to de-aerate whilst filling the formwork and flowing around the reinforcement without any help other than of its self-weight. However, tremie concrete is not equivalent to conventional or to super-workable concrete but fits somewhere in between.

The flow chart in Figure 4 illustrates the basic rheological properties and the quality control requirements of fresh tremie concrete in relation to its workability, stability and its composition. As shown in the chart, the ability of concrete to flow through the gaps in the reinforcement is associated with its “workability” characteristics. The workability parameter measures concrete “flowability” and “passing ability”, where the latter also refers to other such definitions as “deformability” and “blocking resistance”. Similarly, the “workability life” (or the expected performance with time) is rather controlled by the paste and together with the water retention ability they are associated with concrete “stability”. Both, workability and stability are important for concrete quality control. However, during placement the rheological properties and thus the workability of concrete may change with time and by other operational factors. It can alter due to the time requirement to complete the pour or due to a change in the effective hydraulic head. It can also change because of segregation, bleeding, filtration or hydration of the concrete. Thixotropic behaviour might occur in cut-off wall concrete due to the addition of bentonite in the mix. Concrete becomes more “fluid” by stirring or shaking and returns stiffer at decreasing shear rates.

Whilst “concrete workability” is generally considered as an integral property related to most concrete parameters, “concrete stability” is rather controlled by and related to the parameters of rheology and composition of the paste.

Consequently, the addition of suitable admixtures control concrete stability, e.g. they are used to achieve concrete of high strengths at low water cement ratios (w/c). The stability of fresh concrete can be defined by two parameters which need to be determined for each specific application: (1) “Workability Life”, referring to a generic term to indicate the duration required to have concrete of sufficient workability during discharge, placement and pushed to flow further. (2) “Water retention ability”, determines and measures concrete resistance against water loss under pressure.

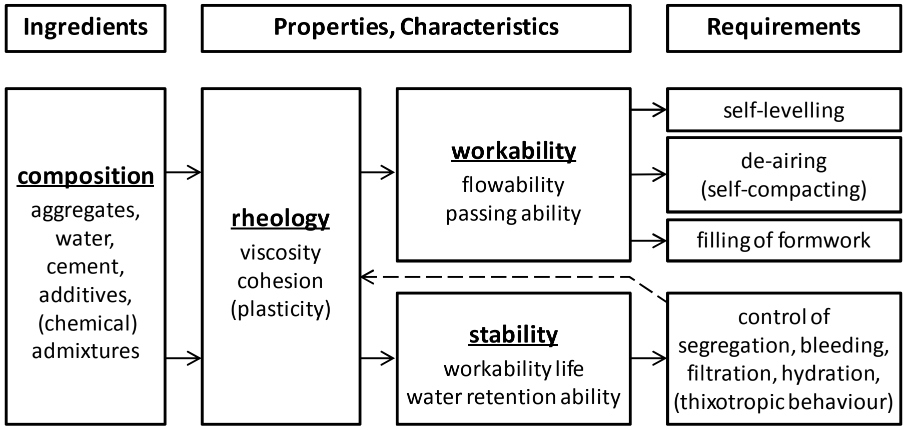

Figure 4. Composition and rheology are directly related to workability and stability

4. Fresh concrete testing

Common testing of fresh concrete is often restricted to the standardized slump test (AS1012.3.1) which had been developed to classify consistency of concrete. The slump test is a very simple test and it has been used successfully over decades to control the required consistency of concrete mixes in laboratories and on site. In terms of rheology parameters slump is supposed to indicate the cohesion of concrete rather than its viscosity or flowability. The slump has never been introduced to characterize concrete of low viscosity or high flowability. Therefore it’s necessary to establish new testing criteria to proof sufficient workability besides slump.

In terms of stability requirements as illustrated in figure 4, the task group members involved in the development of the tremie guide would like to highlight that direct test methods to characterize concrete stability are currently not available.

4.1 Workability

As described above the required workability criteria can’t be identified by the slump test. However, as a global test to measure workability is not available various individual test methods can be carried out, each focusing on a specific property. The new Tremie Concrete Guide will recommend checking sufficient flowability by slump flow or slump spread which can be obtained from the same test procedure (figure 5 - left). If available, the L-Box test will be useful to measure not only flowability but also passing ability (blocking resistance) of a concrete mix in a single test (figure 5 - right).

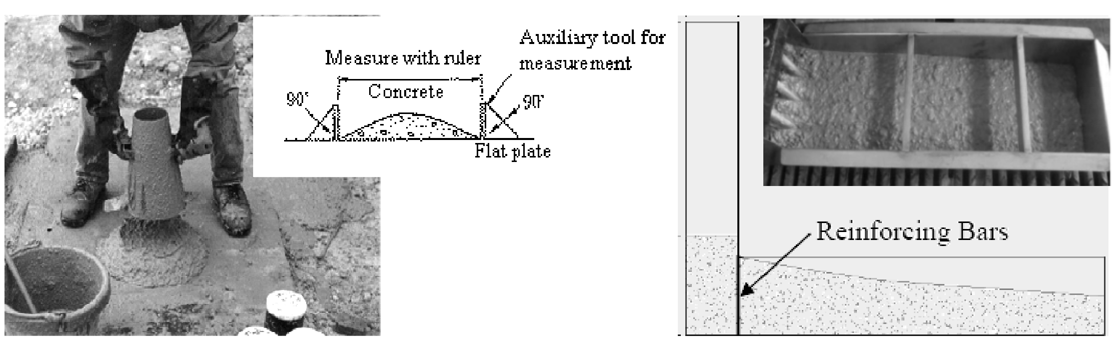

Figure 5: Testing the slump flow, where fresh concrete spreads when lifting the filled cone (left); When opening the gate between the two sections of the L-box, fresh concrete will be discharged through obstructing bars flowing into the horizontal section (right).

4.2 Stability

Slump, slump flow and the L-Box test are suitable to test and identify workability criteria with time which are a function of concrete stability. In particular the L-Box test provides the opportunity to check workability parameters when concrete had been resting for a specified time and is then pushed through obstacles. The behaviour of concrete placed inside a deep excavation can be modelled using this test arrangement.

Bleeding is a particular type of segregation which has to be limited. Common bleeding tests do not take into account hydraulic pressure. However, the BAUER filtration test allows testing concrete stability under more realistic pressure conditions which are present in deep foundations. Test procedure and criteria are specified in the TC Guide.

Another stability issue is hydration of cement. From the first addition of water stiffening, setting and hardening occur as a continuous hydration process. The water cement ratio is the main influence factor for this process. However, stiffening and setting can be controlled by set retarders. Another simple test is recommended to observe changing consistency properties of fresh concrete. The knead bag test seals fresh concrete in a plastic bag and changing consistency phases can be observed by kneading the sample with the fingers, reaching from liquid passing soft to plastic consistency (the latter indicates insufficient workability).

The stability criteria recommended in the TC guide depend on placement conditions (dry or wet pour), on the flow distance and on the maximum depth due to actual hydraulic head pressure which the concrete is subjected to.

5. Example Results from laboratory tests

More than 40 different trial mixes were tested under laboratory conditions as part of this research project. Five trial concrete mixes are displayed and compared in table 1. All five mixes are part of the same series which means that type and distribution of aggregates, cement type and fly ash percentage are constant. All mixes displayed in table 1 demonstrated good water retention abilities. However, water retention was higher with lower water content and in addition with lower w/c ratios. Visually all five mixes were assessed to be of good to excellent workability which might be explained with their relatively high and liquid paste content.

For trial mixes No 1 to 3 the water cement ratio was varied from 0.49 to 0.43. This was achieved by the addition of less water using constant cement contents. Consequently, the paste volume was lower with less water which resulted in the requirement of higher dosages of plasticizing admixtures to achieve good workability and high slump values, which were targeted at about 220 mm for all mixes.

Assessing at the measured values for flowability it is obvious that the visual assessment leads to misjudgement of workability criteria. Mixes No 2 and 3 did not even reach the end of the horizontal section of the L-Box but moved over a considerable long period of about 10 seconds. This might be the result of high pressure applied by the concrete inside vertical section of the L-Box. The measured spread values seem to indicate good flowability as well. A perfect correlation between L-Box time and spread can't be expected because of the obstructions which the concrete has to pass in the L-Box and which obstruct free flow.

Mixes No 3 to 5 (where No 5 is equal to No 4 but includes more plasticiser) have the same w/c ratio of 0.43. For a better lubrication the aggregates of mix No 4 and 5 have more paste achieved by higher quantities of cement and water.

It seems to be proven that at the same type and distribution of aggregates a specific amount of paste must be exceeded to achieve excellent flowability and self levelling criteria. Where 312 l/m^3 paste do not even enable a mix to reach the end of the L-Box, 335 l/m^3 paste allow the concrete to pass the bars at the gate of the L-Box and flow the distance of 600mm within 9 seconds (respectively 4 seconds) only. Trial mix No 5 had a very high slump of 270mm but still showed the same water retention ability than at slump of 230 mm. It did not even show marginal sign of segregation whilst resting in the L-Box (column height is 600mm) for one hour.

Table 1. Data and test results from five selected trial mixes

No	1	2	3	4	5
ID	1.1.1	1.1.3	1.1.6	1.1.7 a	1.1.7 b
cementitious (c)	390 kg	390 kg	390 kg	420 kg	420 kg
water (w)	191 l	179 l	168 l	181 l	181 l
w/c	0.49	0.46	0.43	0.43	0.43
paste volume	335 l/m³	323 l/m³	312 l/m³	335 l/m³	335 l/m³
Slump	240 mm	220 mm	230 mm	230 mm	270 mm
visual assessment of workability	excellent	good	excellent	good	excellent
Spread	500 mm	350 mm	380 mm	390 mm	570 mm
L-Box time	4 s	(11 s)*	(10 s)*	9 s	4 s
L-Box leveling □h	60 mm	(220 mm)*	(170 mm)*	40 mm	20 mm
28 day strength	61 MPa	64 MPa	69 MPa	68 MPa	68 MPa

More results will be analysed and assessed by the task group developping the TC guide.

6. Conclusions

It is crucial to design and maintain concrete mixes for deep foundations which guarantee sufficient workability and stability criteria throughout the entire placement process in order to construct high quality piles and diaphragm walls and to avoid damages and defects within those concrete elements. The control of fresh concrete properties is as important as the achievement of the required mechanical properties of the concrete.

The new TC guide shall assist (1) to design suitable tremie concrete mixes and (2) to proof the required workability and stability parameters such as flowability, passing ability, their performance during placement of concrete and water retention ability. Based on the experience of different stakeholders of the Australian task group and based on an extensive research program investigating behaviour of fresh concrete, specific mix design details such as minimum cement content and paste content are recommended. New testing methods are proposed which might assist to find suitable mixes and to achieve and control sufficient workability and stability. The overall aim of the Tremie Concrete Guide is to recommend suitable compositions, test methods and quality control of tremie concrete. Fresh concrete testing procedures – like the slump test or the slump spread test – can be used to verify the suitability of the appropriate mix.

Several trial mixes with slump values well above 200mm have been successfully tested for applications under water and high flowability requirements. Some trial mixes had slump values of 260mm and these mixes demonstrated excellent performance in regards to stability which leads to the conclusion that concrete with extremely high slump values must not inevitably refused from placement in deep foundations due to potential risks of segregation and stability issues.

The TC guide will be published in late 2011 by the Concrete Institute of Australia.

7. References

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