European Federation of Foundation Contractors (EFFC)
29-31 Elmfield Road
BR1 1LT Bromley
England UK

Deep Foundations Institute (DFI)
318 Walnut Dr.
Venetia, PA 15367
USA

Research report

Subject:	Rheology and Workability Testing of Deep Foundation Concrete in Europe and the US
Client:	European Federation of Foundation Contractors (EFFC)
Project Manager:	Dr.-Ing. Thomas Kränkel

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1. Introduction

1.1 Motivation

Cast in-situ concrete piles and diaphragm walls installed to support excavations or superstructures have to meet structural demands as well as low water permeability. In order to fulfill these basic requirements the fresh concrete must completely fill the cross-section, and fully embed any reinforcing steel. Of course, fresh concrete must also provide sufficient cohesion to avoid excessive segregation or mixing with bentonite, when poured under submerged conditions where the concrete has to displace the supporting fluid.

The fresh concrete also has to maintain a minimum workability upon completion of the placement process, including interruptions or extra working steps like withdrawing temporary casings. With increasing excavation depth, the effect of pressure on the fresh concrete properties has to be considered as well in order to minimize water filtration (or rather pressure-induced bleeding). Water filtration can lead to several types of underperformance like lack of bonding of the reinforcement, zones with a decreased content of cementitious materials and thus worsened mechanical performance or high permeability of the concrete in the cover zone.

To meet the above specified requirements and to ensure acceptable fresh concrete properties, a detailed knowledge on the concrete's flow behavior inside the bored pile or diaphragm wall as well as on the development of the concrete's workability properties over time is essential. Furthermore, a knowledge of the key-factors of the concrete composition on the emerged fresh and hardened performance is of major importance to make distinct recommendations. So far, restrictions are made on the amount of water, cement and fines in order to ensure workability. These values are probably based on outdated experience and lack of knowledge of modern concrete technology since concrete has changed from a 3- to a 5-component material and has thus become a more sophisticated material. Modern concrete technology makes enormous use of the possibility of higher strength and better durability, both related to lower water content, compensated with more chemical admixtures (EFFC/DFI, 2016). The addition of other fines than cement has furthermore increased the variability of fresh concrete properties.

Up to the present, the characterization of the workability, meant to be representative for the rheological properties, is carried out by simple onsite test methods (i.e., slump or spread test). The obvious and major advantage of these methods is the easy handling on site and the fact that these tests are known to almost everybody. However, only a limited spectrum of rheological properties is determinable using these tests. While slump or spread tests (acc. to EN 12390 or ASTM C 143) only permit an indirect characterization of the yield stress, other decisive rheological properties such as viscosity and thixotropy remain unconsidered. Given that the form filling properties of fresh concrete are affected by yield stress as well as viscosity and thixotropy, a reliable prediction based on the common onsite testing is impossible, although in compliance with present standards.

1.2 Aim

The current R&D project deals with the relationship between workability and rheology of deep foundation concrete (“DFC”), and with test methods to assess these properties. The aim is to develop an advanced test concept for the characterization of the fresh DFC on the construction site in order to ensure a more reliable prediction of form filling properties in deep bored piles and diaphragm walls. To ensure the practical applicability, the test concept must be based on easy-to-handle test methods, which enable the determination of the concrete’s flowability and cohesion as a measure of the yield stress and plastic viscosity under site conditions. Furthermore, the test concept shall cover any thixotropic structural build-up, as this may have a significant effect on the form filling properties of the fresh DFC.

Finally, the purpose is to define actual acceptance criteria. The definition of such acceptance criteria shall enable contractors to agree with the concrete supplier on the required fresh concrete properties in a more precise way than at present. Definitive acceptance criteria allow an objective decision to be made at handover on site, determining whether an individual concrete load can be accepted for placement, or has to be rejected. (Kraenkel et al., 2016).

1.3 Scientific Work Program

To develop such an advanced test concept, a step-by-step approach, subdivided in individual work packages was chosen. The objectives and content of the individual work packages (“WP”) are briefly presented below. A more detailed description of the work packages is given in sections 2 - 7.

- **WP 0: Effect of concrete composition on rheology, workability and stability - Literature research**

  The aim of this work package was to collect existing information from literature regarding the effect of the mixture composition of concretes on their rheological behavior. In detail, effects of mixture variations for possible use in DFC were researched, e.g. the effect of the water-to-cementitious ratio (w/c), type of cement, type and amount of additions, type and amount of additives or type and particle size distribution of the aggregates.

- **WP 1a: Workability and Rheology of Deep Foundation Concretes - Testing on construction sites (EU – Test Program)**

  Within this work package DFC should be tested under construction site conditions. The aim was to generate an overview of the workability, stability and rheology of DFC currently used in practical applications within Europe. Both the fresh concrete properties at the time of concrete delivery and their development over time during casting were investigated. The experimental program included the slump flow test (slump, slump flow, slump flow time, VSI), the flow table test (spread and spread flow), L-Box test (flow time and distance, leveling height), Bauer filtration test (water filtration) and vane rheometer test (yield stress, viscosity and thixotropy). In addition, each test was assessed to determine if they were robust enough to deliver useful and repeatable results under on-site conditions.

Construction sites were chosen where the deep foundation elements were later (after hardening) partly excavated in order to assess the quality of the form filling, related to the fresh concrete performance, by a visual inspection (to be done by the contractor).

- **WP 1b: Workability and Rheology of Deep Foundation Concretes - Testing on construction sites (US – Test Program)**

  As for the European investigations, the aim was to generate an overview of the workability, stability and rheology of DFC currently used in practical applications within the US. This enabled the inclusion of findings on the workability and rheology of DFC, based on mixture compositions usually used in the American market within the frame of the current European R&D project.

  In contrast to the European investigations, workability tests on the fresh concretes were performed by the contractors on construction site. The scientific test program on the workability, rheology and stability of the concretes was carried out in the laboratory of the Missouri University of Science and Technology (“Missouri S&T”). The raw materials of the concretes used at the construction sites were therefore delivered to Missouri S&T to enable testing of identical mixture compositions. Compared to the mix designs use on the construction sites, only slight changes in the superplasticizer content were made in order to reach a comparable initial workability. The scope of the test program was comparable to the one in Europe.

- **WP 2: Effect of concrete composition on rheology, workability and stability - Laboratory tests**

  The aim of this work package was to investigate the effect of varying DFC mixtures on their rheology, workability and stability in a more systematic manner. Starting with a reference mixture composition, typical for current DFC in European construction sites, a stepwise exchange or modification of only one component at a time was done and the effect on the initial fresh concrete behavior as well as its development with time (thixotropy and flow retention) was observed. The tested mixture compositions range from ‘good experience mixes’ to ‘bad experience mixes’ to enable the creation of an on-site fresh concrete workability test program and the quantification of related acceptance criteria that ensure a minimum workability and stability for sufficient form filling of the deep foundations.

  Like the experimental program named in WP 1, the program in WP 2 also includes the slump flow test (slump, slump flow, slump flow time, VSI), the flow table test (spread and spread flow), L-Box test (flow time and distance, leveling height), Bauer filtration test (water filtration) and vane rheometer test (yield stress, viscosity and thixotropy).

- **WP 3: Rheology characterization of deep foundation concretes, by means of simple onsite testing**

  The goal of work package 3 was to determine a correlation between onsite workability test parameters and the three major rheological parameters of concrete suspensions, namely: yield stress, viscosity and thixotropy, based on the results of WP 1 and WP 2. With this correlation it is possible to find parameters for a realistic description of concrete flow in deep foundations. These are also used as the basis for the prediction of concrete flow patterns and the related form filling by numerical simulations where rheological parameters have to be set. With a valid correlation between these rheological parameters and the (on construction site) easy to handle workability tests, the required fresh concrete properties can be observed to ensure sufficient form filling. In addition to that, the development of new concrete mixture compositions with customized fresh properties for a given application can be done in the lab using a rheometer and can afterwards be translated into workability test parameters for on-site use.

- **WP 4: Development of a practice-oriented suitability test concept and onsite workability test set for fresh deep foundation concrete based on rheology**

  Work package 4 deals with the development of a set of workability tests, mainly based on existing test methods, and the related acceptance criteria for these tests that ensure a sufficient form filling in deep foundations. The development of this test concept is based on the results of WP 1 regarding the on-site feasibility of the several workability tests (robustness of the test results under on-site conditions) as well as the findings regarding the correlation between the rheological parameters and the workability parameters in WP 3, based on the results of WP 1 and WP 2. A workability test should only be part of the test concept if it is robust enough to deliver useful and especially repeatable results under on-site conditions.

- **WP 5: Requirements related to the mix-design of concrete in deep foundations**

  The aim of this work package is to recommend changes in existing standards based on both the theoretical knowledge gained in WP 0 ‘Effect of concrete composition on rheology, workability and stability - Literature research’ and the experimental results from both WP 1 ‘State of Technology: Workability and Rheology of Deep Foundation Concretes - Testing on Construction Site’ and WP 2 ‘Effect of concrete composition on rheology, workability and stability - Laboratory tests’.

Note: Results from the DFI R&D program, undertaken on US construction sites and in the laboratory of the Missouri S&T, were reviewed and assessed in conjunction with results found in the EFFC R&D program. DFI results are detailed in the report (Feys et al., 2018).

2. WP 0: Effect of concrete composition on rheology, workability and stability - Literature research

2.1 Fundamentals of Concrete Rheology

Concrete rheology is complex and for practical applications (in particular with the final aim to find appropriate test methods to reflect rheological behavior) the physical description has to be simplified. On the other hand, it is mandatory to fully understand the fundamentals of concrete rheology in order to be able to recommend appropriate test methods as it is the overall aim of this R&D project,.

To be continued …

2.2 Effect of concrete composition on rheology, workability and stability

To be done

3. WP1: State of Technology: Workability and Rheology of Deep Foundation Concretes - Testing on Construction Site

3.1 Aim

As the rheology of DFC has not been systematically reviewed using physical parameters before, it was the aim of this WP to collect real data of concrete workability and rheology from actual existing construction sites. The experimental program included the slump flow test (slump, slump flow, slump flow time, VSI), the flow table test (spread and spread flow), L-Box test (flow time and distance, leveling height), Bauer filtration test (water filtration) and vane rheometer test (yield stress, viscosity and thixotropy). In addition, the tests should be checked to ensure they are robust enough to deliver useful and repeatable results under on-site conditions. The experimental program contained both testing of the fresh concrete properties at the time of concrete delivery and the development over time during casting.

The selection of the construction sites for the WP1 was conditional on availability of scientific personnel, sufficient time for pre-planning and also the ability on site to support the scientific team. Furthermore, construction sites were chosen where a partial excavation of the deep foundation elements to assess the quality of the form filling, related to the investigated fresh concrete performance, was planned by a visual inspection, or non-destructive testing (e.g. ultrasonic cross-hole integrity testing) to access the concrete's form filling was planned after hardening.

It was the aim to investigate sites spread over Europe and US, including the execution of bored piles and diaphragm walls. The only requirement to the deep foundation concrete itself was that it should be designed as structural Tremie Concrete and poured submerged, using a tremie pipe.

3.2 Test Program on European Construction Sites

The field test program on European construction sites generally comprised the following tests on fresh concrete:

- Rheology with the vane rheometer
- Spread in accordance with EN 12350-5
- Slump in accordance with EN 12350-2
- Slump flow in accordance with EN 12350-8
- Slump flow velocity
- VSI
- L-Box

- Bauer filtration

As shown in Figure 1, the initial dynamic properties, the initial thixotropic properties (at least 10 minutes after shearing) as well as the flow retention over time (at least 2 hours after concrete arrival on construction site) should be measured and recorded. The majority of the tests were however focused on the rheology and workability. In addition, and to cover a relevant parameter for the stability of concrete, the filtration loss was also tested. All results together may be evaluated and assessed related to the robustness of that specific concrete mix tested.

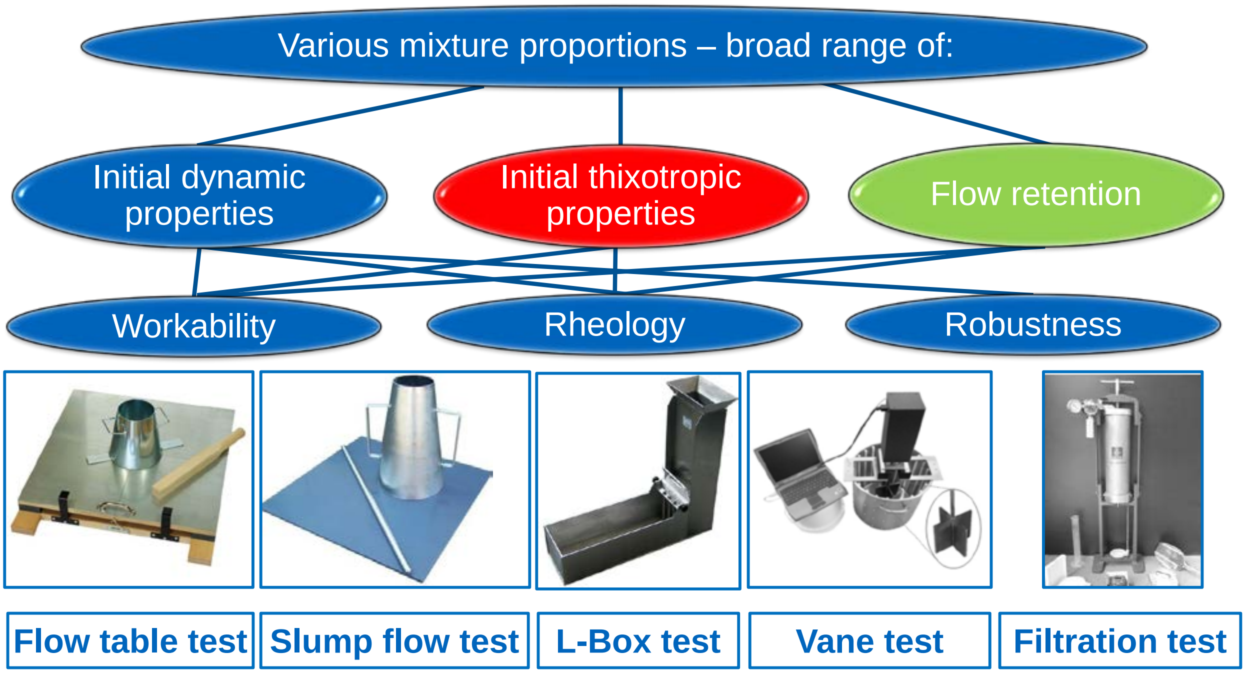

Figure 1: Field test program on European Construction Sites

3.3 Results from European Construction Sites

3.3.1 Bored Piles and Diaphragm-Wall – Producer I

3.3.1.1 General information on the construction site

The first concrete testing on a construction site was carried out on October 20th, 2015 in the Netherlands. Producer I was performing maintenance work on a dike there. Two concrete types were used for this purpose, a concrete type for bored piles and a concrete type for D-Wall elements, see Figure 2. According to Producer I both concretes consist of the same basic mix design, **Table 1**. Only two minor differences regarding the mix design exist: 1) the concrete, produced for the wall elements was retarded for 3 hours and 2) the designated consistency differs. The concrete for the piles was designed in the consistency class F4, the concrete for the wall elements was in F5 both adjusted by varying the superplasticizer content.

Figure 2: Excavation of a D-Wall element of Producer I

3.3.1.2 Concrete details

As mentioned above, the concrete mix design used for both the bored piles and the D-Wall elements was almost identical.

Table 1: Concrete details of Producer I

Mix design	
	Amount [kg/m³]
Cement CEM III/B 42.5 N LH/SR	340
Fly ash	60
Water	180
Sand 0/4 mm	n.v.
Gravel 4/16 mm (rounded)	n.v.
Superplasticizer VC1550	n.v.
Retarder VZ10	n.v.

n.v. = no value available

Characteristic values	
w/c =	0.53
w/(c+0.7f) =	0.47
Remarks:	3 hours retarded (only wall elements)
Designated consistency class:	F4 for piles (spread: 490 - 550 mm) F5 for wall elements (spread: 560 - 620 mm)
Designated cylinder compressive strength:	30 MPa

3.3.1.3 Fresh concrete testing

One batch of the pile concrete and two batches of the D-Wall concrete were tested on the construction site. According to the concrete delivery tickets, the concrete arrival at the construction site was between 45 and 60 minutes after mixing in the plant, see **Table 2**.

Table 2: Concrete delivery times

General Information			
	D-Wall (1)	**Pile**	**D-Wall (2)**
	[hh:mm]	[hh:mm]	[hh:mm]
Indicated time of concrete mixing at the plant:	13:00	13:30	16:05
Arrival on construction site:	13:45	14:30	16:50
Concrete age at arrival on construction site:	00:45	01:00	00:45

One batch of the D-Wall concrete (D-Wall (1)) was fully tested regarding its initial dynamic and thixotropic properties as well as its flow retention during the first three hours (rheometer test 4 hours) after placement. In addition to that, another batch of the D-Wall concrete (D-Wall (2)) as well as a batch of the pile concrete were tested regarding their initial dynamic and thixotropic behavior.

After concrete delivery, a test sample was taken and transported to the test areal using a wheel barrow so that testing could be started round 15 minutes after arrival on construction site. **Table 3** shows the measured values for the initial dynamic concrete behavior.

All three concrete batches showed a higher flowability than expected, demonstrated by the increased spread. Whereas consistency class F4 (490 mm< a < 550 mm) was expected for the pile concrete, a spread of a = 580 mm was measured. The D-Wall concrete was expected in the consistency class F5 (560 mm< a < 620 mm) but exhibited a spread of a = 730 mm and a = 695 mm, respectively. This resulted in an increased slump flow diameter and a reduced dynamic yield stress.

The three tested concrete batches showed a low thixotropy. This can be seen by the low values for the A_{thix}(30-240), **Table 4**. A_{thix}(30-240) is the calculated increase (linear regression) of the static yield stresses with time (between 30 s and 240 s) at rest. Besides A_{thix}(30-240), the slump flow diameter in the slump flow test and the flow distance in the L-Box test showed only minor changes of maximum 10 mm (slump flow) and 30 mm (L-Box flow distance) during time at rest, **Table 4**.

Note: It is remarkable that there was a change in the concrete flow of the pile concrete in the L-Box test between the initial dynamic testing and the test after 240 s at rest. Whereas the concrete reached the end of the L-Box without time at rest, flow motion stopped at a flow distance of 510 mm after 240 s at rest, **Table 4**. This is a first sign, that the L-Box test may not be suitable for practical application if the concrete does not exhibit high flowability, since there is a different measure of the flow behavior before and after the time at rest and both values are hardly comparable.

Table 3: Initial dynamic concrete behavior

Initial dynamic behavior					
			D-Wall (1)	**Pile**	**D-Wall (2)**
Flow table test					
Concrete age at start		[hh:mm]	01:00	01:15	01:00
Spread flow (without hit)	a_0	[mm]	590	385	545
Spread (with15 hits)	a	[mm]	730	580	695
Slump flow test					
Concrete age at start		[hh:mm]	01:10	01:25	01:10
Slump flow	SF	[mm]	645	445	610
Flow time to reach ds,0	t_{SF}	[s]	11.9	8.2	8
Slump flow velocity	v_{SF}	10^{-3} [m/s]	19	25	15
Slump	S	[mm]	265	240	265
VSI	VSI_0	[-]	1	1	1
Vane rheometer test					
Concrete age at start		[hh:mm]	01:20	01:35	01:20
Dynamic yield stress	τ_{0D}	[Pa]	29.6	97.9	59.3
Plastic viscosity	η_{pl}	[Pas]	24.7	25.5	34.4
L-Box test					
Concrete age at start		[hh:mm]	01:30	01:45	01:30
Flow time until end of L-Box	$t_{End,0}$	[s]	1.2	5.1	1.8
Filling height at end of L-Box	h_0	[mm]	80	30	75
Time to end of flowing	$t_{final,0}$	[s]	n.v.	n.v.	n.v.
Maximum flow distance	$d_{final,0}$	[mm]	n.v.	n.v.	n.v.
Bauer filtration test					
Concrete age at start		[hh:mm]	01:45	02:00	01:45
Filtration loss	$t_{End,0}$	[ml]	23	26	21
Filter Cake thickness	h_0	[mm]	115	125	100

Table 4: Thixotropic concrete behavior

<table>
<tr><th colspan="7">Thixotropy</th></tr>
<tr><th colspan="2"></th><th></th><th></th><th>D-Wall (1)</th><th>Pile</th><th>D-Wall (2)</th></tr>
<tr><td colspan="7">**Slump flow test**</td></tr>
<tr><td colspan="2">Concrete age at start</td><td></td><td>[hh:mm]</td><td>01:10</td><td>01:25</td><td>01:10</td></tr>
<tr><td colspan="7">*0 seconds at rest (initial values)*</td></tr>
<tr><td colspan="2">Slump flow</td><td>SF</td><td>[mm]</td><td>645</td><td>445</td><td>610</td></tr>
<tr><td colspan="2">Flow time to reach $d_{s,0}$</td><td>t_{SF}</td><td>[s]</td><td>9.6</td><td>5.0</td><td>12.0</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>v_{SF}</td><td>10^{-3} [m/s]</td><td>23</td><td>25</td><td>17</td></tr>
<tr><td colspan="7">*240 seconds at rest*</td></tr>
<tr><td colspan="2">Slump flow</td><td>SF_{240}</td><td>[mm]</td><td>640</td><td>435</td><td>600</td></tr>
<tr><td colspan="2">Flow time to reach $d_{s,0}$</td><td>$t_{SF,240}$</td><td>[s]</td><td>11.9</td><td>5.5</td><td>13.5</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>$v_{SF,240}$</td><td>10^{-3} [m/s]</td><td>18</td><td>21</td><td>15</td></tr>
<tr><td colspan="7">*Variation during time at rest*</td></tr>
<tr><td colspan="2">Slump flow</td><td>ΔSF</td><td>[mm]</td><td>-5</td><td>-10</td><td>-10</td></tr>
<tr><td colspan="2">Flow time to reach ds,0</td><td>Δt_{SF}</td><td>[s]</td><td>2</td><td>1</td><td>2</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>Δv_{SF}</td><td>10^{-3} [m/s]</td><td>-5</td><td>-3</td><td>-2</td></tr>
<tr><td colspan="7">**Vane rheometer test**</td></tr>
<tr><td colspan="2">Concrete age at start</td><td></td><td>[hh:mm]</td><td>01:20</td><td>01:35</td><td>01:20</td></tr>
<tr><td></td><td>Time at rest [s]</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Static yield stress</td><td>0</td><td>τ_{0S} (0)</td><td>[Pa]</td><td>29.6</td><td>97.9</td><td>59.3</td></tr>
<tr><td>30</td><td>τ_{0S} (30)</td><td>[Pa]</td><td>72.5</td><td>189.6</td><td>124.3</td></tr>
<tr><td>60</td><td>τ_{0S} (60)</td><td>[Pa]</td><td>75.5</td><td>196.0</td><td>136.8</td></tr>
<tr><td>120</td><td>τ_{0S} (120)</td><td>[Pa]</td><td>77.5</td><td>199.0</td><td>158.5</td></tr>
<tr><td>240</td><td>τ_{0S} (240)</td><td>[Pa]</td><td>83.8</td><td>202.0</td><td>177.2</td></tr>
<tr><td colspan="2">Yield stress increase (30 - 240 s)</td><td>A_{thix}(30-240)</td><td>[Pa/s]</td><td>0.05</td><td>0.06</td><td>0.25</td></tr>
<tr><td colspan="7">**L-Box test**</td></tr>
<tr><td colspan="2">Concrete age at start</td><td></td><td>[hh:mm]</td><td>01:30</td><td>01:45</td><td>01:30</td></tr>
<tr><td colspan="7">*0 seconds at rest (initial values)*</td></tr>
<tr><td colspan="2">Flow time until end of L-Box</td><td>$t_{End,0}$</td><td>[s]</td><td>1.2</td><td>5.1</td><td>1.8</td></tr>
<tr><td colspan="2">Filling height at end of L-Box</td><td>h_0</td><td>[mm]</td><td>80</td><td>30</td><td>75</td></tr>
<tr><td colspan="2">Time to end of flowing</td><td>$t_{final,0}$</td><td>[s]</td><td>n.v.</td><td>n.v.</td><td>n.v.</td></tr>
<tr><td colspan="2">Maximum flow distance</td><td>$d_{final,0}$</td><td>[mm]</td><td>n.v.</td><td>n.v.</td><td>n.v.</td></tr>
<tr><td colspan="7">*240 seconds at rest*</td></tr>
<tr><td colspan="2">Flow time until end of L-Box</td><td>$t_{End,240}$</td><td>[s]</td><td>1.7</td><td>n.v.</td><td>2.3</td></tr>
<tr><td colspan="2">Filling height at end of L-Box</td><td>h_{240}</td><td>[mm]</td><td>50</td><td>n.v.</td><td>65</td></tr>
<tr><td colspan="2">Time to end of flowing</td><td>$t_{final,240}$</td><td>[s]</td><td>n.v.</td><td>11.5</td><td>n.v.</td></tr>
<tr><td colspan="2">Maximum flow distance</td><td>$d_{final,240}$</td><td>[mm]</td><td>n.v.</td><td>510</td><td>n.v.</td></tr>
<tr><td colspan="7">*Variation during time at rest*</td></tr>
<tr><td colspan="2">Flow time until end of L-Box</td><td>Δt_{End}</td><td>[s]</td><td>0.5</td><td>n.v.</td><td>0.5</td></tr>
<tr><td colspan="2">Filling height at end of L-Box</td><td>Δh</td><td>[mm]</td><td>-30</td><td>n.v.</td><td>-10</td></tr>
<tr><td colspan="2">Time to end of flowing</td><td>Δt_{final}</td><td>[s]</td><td>n.v.</td><td>n.v.</td><td>n.v.</td></tr>
<tr><td colspan="2">Maximum flow distance</td><td>Δd_{final}</td><td>[mm]</td><td>n.v.</td><td>n.v.</td><td>n.v.</td></tr>
</table>

The concrete batch ‘D-Wall (1)’ was tested regarding its flow retention behavior during three hours (rheometer test until 4 hours) after placement. The test results are given in table 5. The concrete showed good flow retention ability up to two hours at rest which belongs to a total concrete age of around 3 hours. The workability tests after 3 hours at rest resulted in a significantly decreased flowability, the concrete in both the slump cone and the L-Box hold its shape without moving after lifting the cone or opening the gate of the L-Box. In comparison, the vane rheometer showed only a slight increase in yield stress and viscosity for the concrete until four hours after filling the rheometer container (total concrete age around 5.5 hours). This is due to the dynamic measurement in the vane rheometer where the concrete is strongly sheared during the measurement and thus the (within time at rest) built structure can be destroyed.

Table 5: Flow retention behavior of concrete batch D-Wall (1)

Flow retention			
			D-Wall (1)
Slump flow test			
Concrete age at start		[hh:mm]	01:10
0 hours at rest (initial values)			
Slump flow	SF	[mm]	610
Flow time to reach ds,0	t_{SF}	[s]	12
Slump flow velocity	v_{SF}	10^{-3} [m/s]	17
Slump	S	[mm]	265
VSI	VSI	[-]	1
2 hours at rest			
Slump flow	SF_{2h}	[mm]	475
Flow time to reach ds,0	$t_{SF,2h}$	[s]	10
Slump flow velocity	$v_{SF,2h}$	10^{-3} [m/s]	14
Slump	S_{2h}	[mm]	250
VSI	VSI_{2h}	[-]	0
3 hours at rest			
Slump flow	SF_{3h}	[mm]	200*
Flow time to reach ds,0	$t_{SF,3h}$	[s]	n.v.*
Slump flow velocity	$v_{SF,3h}$	10^{-3} [m/s]	n.v.*
Slump	S_{3h}	[mm]	300*
VSI	VSI_{3h}	[-]	0
Vane rheometer test			
Concrete age at start		[hh:mm]	01:20
0 hours at rest (initial values)			
Dynamic yield stress	τ_{0D}	[Pa]	29.6
Plastic viscosity	η_{pl}	[Pas]	24.7
2 hours at rest			
Dynamic yield stress	$\tau_{0D,2h}$	[Pa]	35.9
Plastic viscosity	$\eta_{pl,2h}$	[Pas]	21.9
3 hours at rest			

Table 6: Flow retention behavior of concrete batch D-Wall (1) - CONT.

Flow retention			
			D-Wall (1)
Slump flow test			
Dynamic yield stress	$\tau_{0D,3h}$	[Pa]	51.9
Plastic viscosity	$\eta_{pl,3h}$	[Pas]	24.5
4 hours at rest			
Dynamic yield stress	$\tau_{0D,4h}$	[Pa]	72.8
Plastic viscosity	$\eta_{pl,4h}$	[Pas]	36.2
L-Box test			
Concrete age at start		[hh:mm]	01:30
0 hours at rest (initial values)			
Flow time until end of L-Box	t_{End}	[s]	1.8
Filling height at end of L-Box	h	[mm]	75
Time to end of flowing	t_{final}	[s]	n.v.
Maximum flow distance	d_{final}	[mm]	n.v.
2 hours at rest			
Flow time until end of L-Box	$t_{End,2h}$	[s]	2.1
Filling height at end of L-Box	h_{2h}	[mm]	60
Time to end of flowing	$t_{final,2h}$	[s]	n.v.
Maximum flow distance	$d_{final,2h}$	[mm]	n.v.
3 hours at rest			
Flow time until end of L-Box	$t_{End,3h}$	[s]	n.v.*
Filling height at end of L-Box	h_{3h}	[mm]	n.v.*
Time to end of flowing	$t_{final,3h}$	[s]	n.v.*
Maximum flow distance	$d_{final,3h}$	[mm]	n.v.*

* no more flow behavior

3.3.1.4 Inspection after excavation

There is no information available regarding any visual inspection after excavation. However, there is also no information about any defects nor has an excessive amount of anomalies been reported. Thus it is assumed that the tested concrete led to a positive result with regard to the filling of the excavation, and it was appropriate for the execution process applied and the structural design in place.

3.3.2 Diaphragm-Wall – Producer II

3.3.2.1 General information on the construction site

The second concrete testing was carried out on October 21th, 2015 at a concrete plant in the Netherlands. Producer II was constructing several D-Wall elements at a nearby construction site. The concrete testing could not be carried out on site since the concreting was already completed in September. Although it was planned in the research project, to do the concrete testing directly on site, this concrete should nevertheless be incorporated because it was a very special mix design having an extremely high flowability (designed with a concrete flow diameter in the flow table test of more than 600 mm) with a simultaneously very high water retention capacity.

To enable the comparison between the concrete investigated at the concrete plant (Figure 3) and the form filling properties of the concrete used on site (as to be seen after excavation), both concretes must have comparable workability at the fresh state as well as thixotropy and flow retention. To ensure comparability of these properties, Producer II carried out several workability tests (for example flow table test, slump flow test, L-Box test) with the concrete on site during concreting the D-Wall elements in September.

Figure 3: Testing at the concrete plant

3.3.2.2 Concrete details

Table 6 shows the major details of the concrete mixture composition and the associated characteristic values for the D-Wall concrete under investigation.

Table 7: Concrete details of Producer II

Mix design	
	Amount [kg/m³]
Cement CEM III/B 42.5 N LH/SR	320
Fly ash	40
X10*	32
Water	136
Sand 0/4 mm	842
Gravel 4/16 mm (rounded)	973
Superplasticizer	4.9
Retarder	0.4

Characteristic values	
w/c =	0.43
w/(c+0.7f) =	0.39
Designated consistency class:	F5 (spread: 560 - 620 mm) until F6 (spread: 630 - 690 mm)
Designated cylinder compressive strength:	30 MPa

* No further information on the type of addition given by the producer

3.3.2.3 Fresh concrete testing

For the testing at the concrete plant in October, three batches (each 1.5 m³) of the concrete were prepared and workability, comparable to the range of the concrete workability used on the construction site, was adjusted. To create results comparable to that on the construction site, fresh concrete testing started 50 minutes after mixing in the plant, which was approximately the time needed to transport the concrete from the concrete plant to the construction site, see **Table 8**.

Table 8: Concrete delivery times

General Information			
	Batch 1	**Batch 2**	**Batch 3**
	[hh:mm]	[hh:mm]	[hh:mm]
Time of concrete mixing at the plant:	10:15	12:35	14:55
Start of testing at the concrete plant:	11:05	13:25	15:45
Concrete age at start of testing:	00:50	00:50	00:50

All concretes were fully tested regarding their initial dynamic and thixotropic properties as well as their flow retention during the first two hours (one concrete during the first four hours) after placement. **Table 9** shows the measured values for the initial dynamic concrete behavior.

As expected, the concretes showed high flowability within the designated range. Furthermore, all three batches of the concrete exhibited an outstanding water retention capacity with a filtration loss of only about 7 ml and a filter cake thickness of 20 mm in the Bauer filtration test. The batches showed neither tendency for segregation nor for bleeding.

Table 9: Initial dynamic concrete behavior

Initial dynamic behavior					
			Batch 1	**Batch 2**	**Batch 3**
Flow table test					
Concrete age at start		[hh:mm]	00:50	00:50	00:50
Spread flow (without hit)	a_0	[mm]	350	560	525
Spread (with15 hits)	a	[mm]	600	660	635
Slump flow test					
Concrete age at start		[hh:mm]	01:00	01:00	01:00
Slump flow	SF	[mm]	410	670	590
Flow time to reach ds,0	t_{SF}	[s]	13.0	16.0	16.0
Slump flow velocity	v_{SF}	10^{-3} [m/s]	8	15	12
Slump	S	[mm]	230	270	265
VSI	VSI_0	[-]	0	0	0
Vane rheometer test					
Concrete age at start		[hh:mm]	01:10	01:10	01:10
Dynamic yield stress	τ_{0D}	[Pa]	138	33	54
Plastic viscosity	η_{pl}	[Pas]	45.7	29.5	35.8
L-Box test					
Concrete age at start		[hh:mm]	01:20	01:20	01:20
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.	2	3.1
Filling height at end of L-Box	h_0	[mm]	n.v.	95	90
Time to end of flowing	$t_{final,0}$	[s]	24.0	n.v.	n.v.
Maximum flow distance	$d_{final,0}$	[mm]	330	n.v.	n.v.
Bauer filtration test					
Concrete age at start		[hh:mm]	01:35	01:35	01:35
Filtration loss	$t_{End,0}$	[ml]	6.8	6.8	6.3
Filter Cake thickness	h_0	[mm]	20	20	20

Note: It is important to note that the 1st Batch of the concrete did not reach the end of the horizontal section of the L-Box even in the fresh state, although it has a slump flow of 410 mm which is in a usual range for tremie concretes. Batches 2 and 3 reached the end within a few seconds. This is another indication that L-Box test may not be suitable for practical application since there is a different measure of the flow behavior (time to reach the end of the L-Box versus flow distance in the horizontal section) for the same concrete mix design depending on its flowability and these two measures are not comparable.

Table 9 shows the measured values for the thixotropic behavior of the three concrete batches.

Table 10: Thixotropic concrete behavior

Thixotropy						
				Batch 1	Batch 2	Batch 3
Slump flow test						
Concrete age at start			[hh:mm]	01:00	01:00	01:00
0 seconds at rest (initial values)						
Slump flow		SF	[mm]	410	670	590
Flow time to reach $d_{s,0}$		t_{SF}	[s]	13.0	16.0	16.0
Slump flow velocity		v_{SF}	10^{-3} [m/s]	8	15	12
240 seconds at rest						
Slump flow		SF_{240}	[mm]	380	650	575
Flow time to reach $d_{s,0}$		$t_{SF,240}$	[s]	13.5	18.0	17.0
Slump flow velocity		$v_{SF,240}$	10^{-3} [m/s]	7	13	11
Variation during time at rest						
Slump flow		ΔSF	[mm]	-30	-20	-15
Flow time to reach ds,0		Δt_{SF}	[s]	0.5	2	1
Slump flow velocity		Δv_{SF}	10^{-3} [m/s]	-1	-2	-1
Vane rheometer test						
Concrete age at start			[hh:mm]	01:10	01:10	01:10
	Time at rest [s]					
Static yield stress	0	τ_{0S} (0)	[Pa]	138	33	54
	30	τ_{0S} (30)	[Pa]	377	141	184
	60	τ_{0S} (60)	[Pa]	432	189	259
	120	τ_{0S} (120)	[Pa]	492	251	291
	240	τ_{0S} (240)	[Pa]	542	315	361
Yield stress increase (30 - 240 s)		A_{thix}(30-240)	[Pa/s]	0.79	0.83	0.84
L-Box test						
Concrete age at start			[hh:mm]	01:20	01:20	01:20
0 seconds at rest (initial values)						
Flow time until end of L-Box		$t_{End,0}$	[s]	n.v.	2.0	3.1
Filling height at end of L-Box		h_0	[mm]	n.v.	95	90
Time to end of flowing		$t_{final,0}$	[s]	24.0	n.v.	n.v.
Maximum flow distance		$d_{final,0}$	[mm]	330	n.v.	n.v.
240 seconds at rest						
Flow time until end of L-Box		$t_{End,240}$	[s]	n.v.	2.6	3.3
Filling height at end of L-Box		h_{240}	[mm]	n.v.	85	80
Time to end of flowing		$t_{final,240}$	[s]	19.0	n.v.	n.v.
Maximum flow distance		$d_{final,240}$	[mm]	270	n.v.	n.v.
Variation during time at rest						
Flow time until end of L-Box		Δt_{End}	[s]	n.v.	0.6	0.2
Filling height at end of L-Box		Δh	[mm]	n.v.	-10	-10
Time to end of flowing		Δt_{final}	[s]	-5.0	n.v.	n.v.
Maximum flow distance		Δd_{final}	[mm]	-60	n.v.	n.v.

The three tested concrete batches showed a pronounced thixotropy. This can be seen by the high values for the A_{thix}(30-240), **Table 9**. Besides A_{thix}(30-240), the slump flow showed a decrease of up to 30 mm (slump flow) during 4 minutes at rest, **Table 9**. In contrast, the L-Box test does not show that pronounced thixotropic structuration as to be seen in the merely slight changes in flow time and filling height for Batches 2 and 3. The experiments regarding the thixotropic structural build up in Batch 1 show a decrease in the time needed to reach the final flow distance after time at rest. This is mainly affected by the decreased value for the flow distance after time at rest (- 60 mm, **Table 9**).

All three concrete batches showed good flow retention properties, as to be seen in the moderate increase in yield stress and viscosity even four hours after start of the testing, **Table 10**.

Note: The slump flow test shows a pronounced decrease of workability over time (especially for Batch 1 due to its low initial slump flow) which is unexpected with regard to the vane rheometer measurements. The concrete was filled in the truncated cones at the beginning of fresh concrete testing an let at rest for 2, 3 or rather 4 h, whereas the concrete in the vane rheometer was sheared during the measurement, this pronounced workability loss can therefore be linked to a thixotropic structuration process.

On this basis, slump flow testing without agitating (remixing) the concrete before testing may be too critical for the flow retention behavior of tremie concrete. This implies that for practical relevance the concrete has to be sufficiently sheared in the deep foundation elements to retain its required workability until it is finally placed.

Table 11: Flow retention behavior

Flow retention					
			Batch 1	**Batch 2**	**Batch 3**
Slump flow test					
Concrete age at start		[hh:mm]	01:00	01:00	01:00
0 hours at rest (initial values)					
Slump flow	SF	[mm]	410	670	590
Flow time to reach ds,0	t_{SF}	[s]	13.0	16.0	16.0
Slump flow velocity	v_{SF}	10^{-3} [m/s]	8	15	12
Slump	S	[mm]	230	270	265
VSI	VSI	[-]	0	0	0
2 hours at rest					
Slump flow	SF_{2h}	[mm]	200*	520	425
Flow time to reach ds,0	$t_{SF,2h}$	[s]	n.v.*	23.0	19.6
Slump flow velocity	$v_{SF,2h}$	10^{-3} [m/s]	n.v.*	7	6
Slump	S_{2h}	[mm]	300*	250	235
VSI	VSI_{2h}	[-]	0	0	0
4 hours at rest					

Table 12: Flow retention behavior - CONT.

Flow retention					
			Batch 1	**Batch 2**	**Batch 3**
Slump flow	SF_{4h}	[mm]	200*	425	200*
Flow time to reach ds,0	$t_{SF,4h}$	[s]	n.v.*	23.0	n.v.*
Slump flow velocity	$v_{SF,4h}$	10^{-3} [m/s]	n.v.*	5	n.v.*
Slump	S_{4h}	[mm]	300*	235	300*
VSI	VSI_{4h}	[-]	0	0	0
Vane rheometer test					
Concrete age at start		[hh:mm]	01:10	01:10	01:10
0 hours at rest (initial values)					
Dynamic yield stress	τ_{0D}	[Pa]	138	33	54
Plastic viscosity	η_{pl}	[Pas]	45.7	29.5	35.8
2 hours at rest					
Dynamic yield stress	$\tau_{0D,2h}$	[Pa]	202	60	97
Plastic viscosity	$\eta_{pl,2h}$	[Pas]	44.3	39.0	54.3
3 hours at rest					
Dynamic yield stress	$\tau_{0D,3h}$	[Pa]	211	78	n.v.
Plastic viscosity	$\eta_{pl,3h}$	[Pas]	46.1	44.3	n.v.
4 hours at rest					
Dynamic yield stress	$\tau_{0D,4h}$	[Pa]	260	92	n.v.
Plastic viscosity	$\eta_{pl,4h}$	[Pas]	52.8	41.5	n.v.
L-Box test					
Concrete age at start		[hh:mm]	01:20	01:20	01:20
0 hours at rest (initial values)					
Flow time until end of L-Box	t_{End}	[s]	n.v.	2	3.1
Filling height at end of L-Box	h	[mm]	n.v.	95	90
Time to end of flowing	t_{final}	[s]	24.0	n.v.	n.v.
Maximum flow distance	d_{final}	[mm]	330	n.v.	n.v.
2 hours at rest					
Flow time until end of L-Box	$t_{End,2h}$	[s]	n.v.*	8.1	6.7
Filling height at end of L-Box	h_{2h}	[mm]	n.v.*	75	65
Time to end of flowing	$t_{final,2h}$	[s]	n.v.*	n.v.	n.v.
Maximum flow distance	$d_{final,2h}$	[mm]	n.v.*	n.v.	n.v.
4 hours at rest					
Flow time until end of L-Box	$t_{End,4h}$	[s]	n.v.*	6.1	n.v.
Filling height at end of L-Box	h_{4h}	[mm]	n.v.*	60	n.v.
Time to end of flowing	$t_{final,4h}$	[s]	n.v.*	n.v.	n.v.
Maximum flow distance	$d_{final,4h}$	[mm]	n.v.*	n.v.	n.v.

* no more flow behavior

3.3.2.4 Inspection after excavation

The excavation of the D-Wall elements took place in January 2016. Figure 4 to Figure 6 show the surface quality of the element after excavation and cleaning. It is obvious that the concrete showed a good form filling behavior. No imperfections can be seen. Some slight wash-out effects can be seen on the concrete surface, but no inclusions, no mattressing and no channeling, see Figure 6.

Figure 4: D-Wall element of Producer II after excavation

Figure 5: D-Wall element of Producer II after excavation (detail)

Figure 6: D-Wall element of Producer II after excavation (detail)

Figure 7: Core drilling in the D-Wall element of Producer II

In addition to the visual inspection, cores were drilled out of the D-Wall elements in order to determine the concrete compressive strength but also to gain some information on the homogeneity of the concrete within the element, Figure 7.

Until now, there are no results for the drilled cores delivered for implementation in that report.

3.3.3 Bored piles – Producer III

3.3.3.1 General information on the construction site

Concrete testing was planned to be carried out on November 17th, 2015 in UK. Producer **III** built a foundation for a 60-storey residential skyscraper, Figure 8. It was planned to test a C40/50 and a C32/40 concrete, both to be used for bored piles. Due to difficulties in the excavation process, only concrete mix design C32/40 was delivered for one secondary pile on this day. Only one batch of this concrete could be tested. This is not sufficient for a representative assessment of the fresh concrete properties needed for comparison with the form filling ability in the pile on site. It was therefore decided to repeat concrete testing for Producer **III** at another point in time.

Figure 8 Overview of the construction site of Producer **III**

3.3.4 D-Wall – Producer IV

3.3.4.1 General information on the construction site

During the first trip to UK, concrete testing on a construction site of Producer IV was planned to be carried out on November 18th, 2015. The aim of the construction site was to build a station box of a new underground station, Figure 9. Contrary to expectations no concrete arrived during out site visit also due to difficulties in the excavation process. It was therefore decided to repeat concrete testing for Producer IV at another time as well.

Figure 9: Excavation of a station box

3.3.5 D-Wall – Producer III (2nd testing)

3.3.5.1 General information on the construction site

The second trial for concrete testing for Producer III took place in the UK again, Figure 10. Preliminary testing of the concrete was carried out on June 21st, 2016 and full testing on June 23rd, 2016. Two concrete suppliers alternately delivered concrete for the bored piles built during these two days.

Figure 10: Testing area at the construction site of Producer III

3.3.5.2 Concrete details

The mixture composition of the concretes of both suppliers was comparable regarding their mix design (except admixtures), designed cylinder compressive strength was 32 MPa and designed consistency class was F5, which corresponds to a spread in the range from 560 mm to 620 mm, compare **Table 11**.

Table 13: Concrete details of Producer III

Mix design		
	Supplier 1	Supplier 2
	Amount [kg/m^3]	
Cement CEM III/A 42.5 N LH/SR	233	
GGBS	233	
Water	209	
Sand 0/4 mm	729	
Gravel 4/10 mm (crushed)	997	
Superplasticizer	0.5	n.v.*
Retarder	0.5	n.v.*

Characteristic values	
w/c =	0.93
w/(c+0.7ggbs) =	0.55
Designated consistency class:	F5 (spread: 560 - 620 mm)
Designated cylinder compressive strength:	32 MPa

* No information found at the concrete delivery ticket

3.3.5.3 Fresh concrete testing

Three batches from each concrete supplier were tested on the construction site. Batch 3 of Supplier 1 and Batch 2 and 3 of Supplier 2 were used for preliminary testing on June 21st. No flow retention tests were run during this preliminary testing. Concrete Batches 1 and 2 of Supplier 1 as well as Batch 1 of Supplier 2 were fully tested regarding its initial dynamic, its thixotropic and its flow retention behavior.

According to the concrete delivery tickets, the concrete arrival at construction site was between 25 and 75 minutes after mixing in the plant, see **Table 12**. Batch 2 of Supplier 1 reached the construction site after one and a quarter hours due to a traffic jam.

Table 14: Concrete delivery times

General Information						
	Supplier 1			**Supplier 2**		
	Batch 1	**Batch 2**	**Batch 3**	**Batch 1**	**Batch 2**	**Batch 3**
	[dd:mm:jj hh:mm]	[dd:mm:jj hh:mm]	[dd:mm:jj hh:mm]	[dd:mm:jj hh:mm]	[dd:mm:jj hh:mm]	[dd:mm:jj hh:mm]
Indicated time of concrete mixing at the plant:	23:06:16 08:55	23:06:16 12:05	21:06:16 11:40	23:06:16 10:10	21:06:16 10:15	21:06:16 12:35
Arrival on construction site:	09:20	13:20	12:15	10:45	11:00	13:05
Concrete age at arrival on construction site:	00:25	01:15	00:35	00:35	00:45	00:30

It was noticeable that the two concretes used for the same bored pile during full testing on June 23rd, 2016 differed significantly in their delivered consistency, see **Table 13**. Whereas Supplier 1 delivered concrete with a mean spread value of about 615 mm (average of Batch 1 and 2), Supplier 2 delivered concrete with a spread value of only about 520 mm (Batch 1). Hence the viscosity of the concrete differed significantly as well. The highly flowable concrete exhibits a low viscosity whereas the stiffer concrete was highly viscous.

All tested concretes showed tendencies to lose high amounts of water of up to 31 ml (filter cake thickness up to 165 mm) in the Bauer filtration test. In contrast they showed no visual tendency for segregation or bleeding.

Table 15: Initial dynamic concrete behavior

Initial dynamic behavior								
			Supplier 1			**Supplier 2**		
			Batch 1	**Batch 2**	**Batch 3**	**Batch 1**	**Batch 2**	**Batch 3**
Flow table test								
Concrete age at start		[hh:mm]	00:35	01:25	00:45	00:50	01:00	00:45
Spread flow (without hit)	a_0	[mm]	550	380	450	310	445	540
Spread (with15 hits)	a	[mm]	650	580	555	520	620	640
Slump flow test								
Concrete age at start		[hh:mm]	00:45	01:35	00:55	01:00	01:10	00:55
Slump flow	SF	[mm]	535	425	390	350	500	515
Flow time to reach ds,0	t_{SF}	[s]	3.9	0.8	0.9	8.1	3.5	4.3
Slump flow velocity	v_{SF}	10^{-3} [m/s]	43	141	106	9	43	37
Slump	S	[mm]	270	230	250	205	250	265
VSI	VSI_0	[-]	0	0	0	0	0	0
Vane rheometer test								
Concrete age at start		[hh:mm]	00:55	01:45	01:05	01:10	01:20	01:05
Dynamic yield stress	τ_{0D}	[Pa]	92	174	210	358	110	90
Plastic viscosity	η_{pl}	[Pas]	19.5	12.0	14.0	56.4	20.0	24.0
L-Box test								
Concrete age at start		[hh:mm]	01:05	01:55	01:15	01:20	01:30	01:15
Flow time until end of L-Box	$t_{End,0}$	[s]	1.4	1.0	3.6	n.v.	n.v.	n.v.
Filling height at end of L-Box	h_0	[mm]	70	50	5	n.v.	n.v.	n.v.
Time to end of flowing	$t_{final,0}$	[s]	n.v.	n.v.	n.v.	10.1	n.v.	n.v.
Maximum flow distance	$d_{final,0}$	[mm]	n.v.	n.v.	n.v.	525	n.v.	n.v.
Bauer filtration test								
Concrete age at start		[hh:mm]	01:15	02:05	01:25	01:30	01:40	01:25
Filtration loss	$t_{End,0}$	[ml]	31	27	n.v.	22	n.v.	30
Filter Cake thickness	h_0	[mm]	165	140	n.v.	140	n.v.	150

Table 14 shows the measured values for the thixotropic behavior of the concrete batches. It I noticeable that measurements after 600 s undisturbed at rest were done in addition or rather instead of the tests after 240 s at rest. This was due to the fact that there were only minor changes in the measured values between the initial testing and the measurement after 240 s at rest for most of th concretes under investigation within this R&D project (especially in the lab test series of WP 2).

Table 16: Thixotropic concrete behavior

Thixotropy								
			Supplier 1			**Supplier 2**		
			Batch 1	**Batch 2**	**Batch 3**	**Batch 1**	**Batch 2**	**Batch 3**
Slump flow test								
Concrete age at start		[hh:mm]	00:45	01:35	00:55	01:00	01:10	00:55
0 seconds at rest (initial values)								
Slump flow	SF	[mm]	535	425	390	350	500	515
Flow time to reach $d_{s,0}$	t_{SF}	[s]	3.9	0.8	0.9	8.1	3.5	4.3
Slump flow velocity	v_{SF}	10^{-3} [m/s]	43	141	106	9	43	37
240 seconds at rest								
Slump flow	SF_{240}	[mm]	500	390	n.v.	330	n.v.	n.v.
Flow time to reach $d_{s,0}$	$t_{SF,240}$	[s]	3.7	1.0	n.v.	8.9	n.v.	n.v.
Slump flow velocity	$v_{SF,240}$	10^{-3} [m/s]	41	95	n.v.	8	n.v.	n.v.
Variation during time at rest								
Slump flow	ΔSF	[mm]	-35	-35	n.v.	-20	n.v.	n.v.
Flow time to reach ds,0	Δt_{SF}	[s]	-0.2	0.2	n.v.	0.8	n.v.	n.v.
Slump flow velocity	Δv_{SF}	10^{-3} [m/s]	-2	-46	n.v.	-1	n.v.	n.v.
600 seconds at rest								
Slump flow	SF_{600}	[mm]	460	375	345	310	445	445
Flow time to reach $d_{s,0}$	$t_{SF,600}$	[s]	3.9	1.1	1.1	8.9	4.0	5.3
Slump flow velocity	$v_{SF,600}$	10^{-3} [m/s]	33	80	66	6	31	23
Variation during time at rest								
Slump flow	ΔSF	[mm]	-75	-50	-45	-40	-55	-70
Flow time to reach ds,0	Δt_{SF}	[s]	0.4	0.3	0.2	0.8	0.5	1.0
Slump flow velocity	Δv_{SF}	10^{-3} [m/s]	-15	-61	-40	-3	-12	-14

Table 17: Thixotropic concrete behavior – CONT.

Thixotropy									
				Supplier 1			Supplier 2		
				Batch 1	Batch 2	Batch 3	Batch 1	Batch 2	Batch 3
Vane rheometer test									
Concrete age at start			[hh:mm]	00:55	01:45	01:05	01:10	01:20	01:05
	Time at rest [s]								
Static yield stress	0	τ_{0S} (0)	[Pa]	92	174	210	358	110	90
	30	τ_{0S} (30)	[Pa]	146	536	n.v.	1817	n.v.	n.v.
	60	τ_{0S} (60)	[Pa]	170	608	n.v.	1926	n.v.	n.v.
	120	τ_{0S} (120)	[Pa]	208	664	n.v.	2067	n.v.	n.v.
	240	τ_{0S} (240)	[Pa]	258	819	n.v.	2302	n.v.	n.v.
	600	τ_{0S} (600)	[Pa]	353	1129	n.v.	2826	n.v.	n.v.
Yield stress increase (30 - 240 s)		A_{thix}(30-240)	[Pa/s]	0.5	1.3	n.v.	2.3	n.v.	n.v.
L-Box test									
Concrete age at start			[hh:mm]	01:05	01:55	01:15	01:20	01:30	01:15
0 seconds at rest (initial values)									
Flow time until end of L-Box		$t_{End,0}$	[s]	1.4	1.0	3.6	n.v.	n.v.	n.v.
Filling height at end of L-Box		h_0	[mm]	70	50	5	n.v.	n.v.	n.v.
Time to end of flowing		$t_{final,0}$	[s]	n.v.	n.v.	n.v.	10.1	n.v.	n.v.
Maximum flow distance		$d_{final,0}$	[mm]	n.v.	n.v.	n.v.	525	n.v.	n.v.
600 seconds at rest									
Flow time until end of L-Box		$t_{End,600}$	[s]	2.6	1.5	n.v.	n.v.	n.v.	n.v.
Filling height at end of L-Box		h_{600}	[mm]	45	30	n.v.	n.v.	n.v.	n.v.
Time to end of flowing		$t_{final,600}$	[s]	n.v.	n.v.	6.3	13.3	n.v.	n.v.
Maximum flow distance		$d_{final,600}$	[mm]	n.v.	n.v.	530	470	n.v.	n.v.
Variation during time at rest									
Flow time until end of L-Box		Δt_{End}	[s]	1.2	0.5	n.v.	n.v.	n.v.	n.v.
Filling height at end of L-Box		Δh	[mm]	-25	-20	n.v.	n.v.	n.v.	n.v.
Time to end of flowing		Δt_{final}	[s]	n.v.	n.v.	n.v.	3.2	n.v.	n.v.
Maximum flow distance		Δd_{final}	[mm]	n.v.	n.v.	n.v.	-55	n.v.	n.v.

All tested concrete batches showed a pronounced thixotropy. This can be seen by the high values for the A_{thix}(30-240), **Table 14**. In addition to that, the slump flow showed a pronounced decrease of up to 35 mm (240 s at rest) or rather 75 mm (600 s at rest), **Table 14**. In this test series, the L-Box test also showed significant changes but as well the weak spot of that test method in order to quantify thixotropy since one batch

(Supplier 1, Batch 3) reached the end of the horizontal section of the L-Box without time at rest but not after 600 s at rest. Thus it is impossible to quantify a measure for thixotropy.

Tests to quantify the flow retention behavior of the concretes were only done during full testing on June 23rd, 2016. Results can be seen in **Table 15**.

Both concretes showed a pronounced workability loss. After two hours at rest, the concrete retained its shape after lifting the slump flow cone and remained in the vertical compartment of the L-Box after lifting the lock. Even after remixing the concrete (corresponding to the usual flow retention test) workability could not be restored.

Table 18: Flow retention behavior

Flow retention					
			Supplier 1		**Supplier 2**
			Batch 1	**Batch 2**	**Batch 1**
Slump flow test					
Concrete age at start		[hh:mm]	00:45	01:35	01:00
0 hours at rest (initial values)					
Slump flow	SF	[mm]	535	425	350
Flow time to reach ds,0	t_{SF}	[s]	3.9	0.8	8.1
Slump flow velocity	v_{SF}	10^{-3} [m/s]	43	141	9
Slump	S	[mm]	270	230	205
VSI	VSI	[-]	0	0	0
2 hours at rest					
Slump flow	SF_{2h}	[mm]	200*	200*	200*
Flow time to reach ds,0	$t_{SF,2h}$	[s]	n.v.*	n.v.*	n.v.*
Slump flow velocity	$v_{SF,2h}$	10^{-3} [m/s]	n.v.*	n.v.*	n.v.*
Slump	S_{2h}	[mm]	300*	300*	300*
VSI	VSI_{2h}	[-]	0	0	0
Vane rheometer test					
Concrete age at start		[hh:mm]	00:55	01:45	01:10
0 hours at rest (initial values)					
Dynamic yield stress	τ_{0D}	[Pa]	92	174	358
Plastic viscosity	η_{pl}	[Pas]	19.5	12.0	56.4
2 hours at rest					
Dynamic yield stress	$\tau_{0D,2h}$	[Pa]	237	n.v.	943
Plastic viscosity	$\eta_{pl,2h}$	[Pas]	29.5	n.v.	67.4
L-Box test					
Concrete age at start		[hh:mm]	01:05	01:55	01:20
0 hours at rest (initial values)					
Flow time until end of L-Box	t_{End}	[s]	1.4	1.0	n.v.
Filling height at end of L-Box	h	[mm]	70	50	n.v.
Time to end of flowing	t_{final}	[s]	n.v.	n.v.	10.1
Maximum flow distance	d_{final}	[mm]	n.v.	n.v.	525
2 hours at rest					
Flow time until end of L-Box	$t_{End,2h}$	[s]	n.v.*	n.v.*	n.v.*
Filling height at end of L-Box	h_{2h}	[mm]	n.v.*	n.v.*	n.v.*
Time to end of flowing	$t_{final,2h}$	[s]	n.v.*	n.v.*	n.v.*
Maximum flow distance	$d_{final,2h}$	[mm]	n.v.*	n.v.*	n.v.*

* no more flow behavior

3.3.5.4 Inspection after excavation

An ultrasonic crosshole integrity assessment in accordance with ASTM D6760-14 was performed instead of the originally planned visual inspection. The purpose of the assessment was to check the continuity of the installed piles (2 piles, where the investigated fresh concrete was used) and to identify significant anomalies that may be present within the capabilities of ultrasonic crosshole methods.

Figure 11 shows the tube orientation within the pile and Figure 12 the recorded first arrival times (FAT) and the signal attenuation for one of the two piles under investigation. Both FAT and signal attenuation are criteria to evaluate the continuity of the pile. Figure 12 indicates, that there are no significant discontinuities since FAT and signal attenuation are consistent over the full length of the tubes.

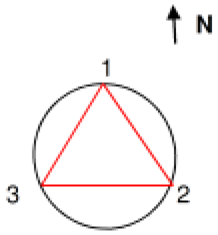

Figure 11: Tube orientation for the piles under investigation

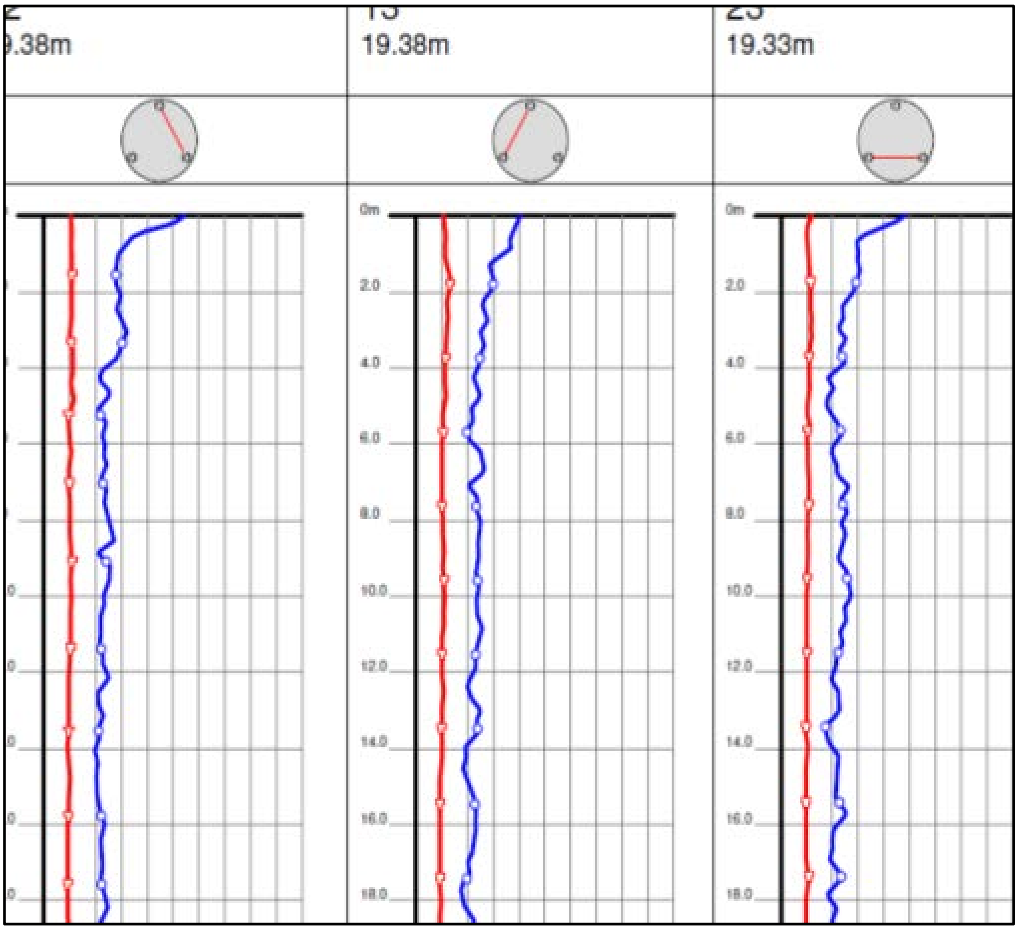

Figure 12: Sonic logging profiles between tubes 1 – 2, 1 – 3 and 2 – 3 of one of the two investigated piles

3.3.6 D-Wall – Producer IV (2nd testing)

3.3.6.1 General information on the construction site

The second trial for concrete testing for Producer IV was again in the UK; compare section 3.3.4, p. 26 for further information. Concrete testing was carried out on June 22nd, 2016. The concrete which was placed on this day was for a D-Wall panel, Figure 13.

Figure 13: Concrete placement for a D-Wall panel

3.3.6.2 Concrete details

The investigated concrete had a designed cylinder compressive strength of 32 MPa and a spread value between 560 mm to 620 mm (consistency class F5), see **Table 16**.

Table 19: Concrete details of Producer IV

Mix design	
	Amount [kg/m³]
Cement CEM III/A 42.5 N LH/SR	380
Water	152
Sand 0/4 mm	n.v.*
Gravel 4/20 mm (crushed)	n.v.*
Superplasticizer	n.v.*

Characteristic values	
w/c =	0.40
Designated consistency class:	F5 (spread: 560 - 620 mm)
Designated cylinder compressive strength:	32 MPa

* No information regarding the amount found on the concrete delivery ticket

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3.3.6.3 Fresh concrete testing

Fresh concrete testing started around 30 minutes after mixing in the plant, see **Table 7**.

Table 20: Concrete delivery times

General Information			
	Batch 1	**Batch 2**	**Batch 3**
	[hh:mm]	[hh:mm]	[hh:mm]
Time of concrete mixing at the plant:	13:10	15:10	17:10
Start of testing at the concrete plant:	13:40	15:45	17:35
Concrete age at start of testing:	00:30	00:35	00:25

The concrete was fully tested three times regarding its initial dynamic and thixotropic properties as well as its flow retention up to four hours after placement. **Table 18** shows the measured values for the initial dynamic concrete behavior.

Table 21: Initial dynamic concrete behavior

Initial dynamic behavior					
			Batch 1	**Batch 2**	**Batch 3**
Flow table test					
Concrete age at start		[hh:mm]	00:40	00:45	00:35
Spread flow (without hit)	a_0	[mm]	425	440	520
Spread (with15 hits)	a	[mm]	580	620	650
Slump flow test					
Concrete age at start		[hh:mm]	00:50	00:55	00:45
Slump flow	SF	[mm]	455	510	550
Flow time to reach ds,0	t_{SF}	[s]	5.2	10.9	7.0
Slump flow velocity	v_{SF}	10^{-3} [m/s]	25	14	25
Slump	S	[mm]	250	255	255
VSI	VSI_0	[-]	0	0	0
Vane rheometer test					
Concrete age at start		[hh:mm]	01:00	01:05	00:55
Dynamic yield stress	τ_{0D}	[Pa]	139	103	61
Plastic viscosity	η_{pl}	[Pas]	29.0	39.0	29.0
L-Box test					
Concrete age at start		[hh:mm]	01:10	01:15	01:05
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.	4.9	3.0
Filling height at end of L-Box	h_0	[mm]	n.v.	60	70
Time to end of flowing	$t_{final,0}$	[s]	11.5	n.v.	n.v.
Maximum flow distance	$d_{final,0}$	[mm]	580	n.v.	n.v.
Bauer filtration test					
Concrete age at start		[hh:mm]	01:20	01:25	01:15
Filtration loss	$t_{End,0}$	[ml]	15	13	14
Filter Cake thickness	h_0	[mm]	60	55	65

The concrete showed a good workability after arrival on site. The measured consistency (spread value, slump flow) of the concrete was as per the design. The viscosity of the concrete was moderate, demonstrated by intermediate values of the flow velocity during testing, e.g. the time to reach the end of the horizontal compartment in the L-Box test.

Table 19 shows the measured values for the thixotropic behavior of the three concrete batches.

Table 22: Thixotropic concrete behavior

Thixotropy						
				Batch 1	**Batch 2**	**Batch 3**
Slump flow test						
Concrete age at start			[hh:mm]	00:50	00:55	00:45
0 seconds at rest (initial values)						
Slump flow		SF	[mm]	455	510	550
Flow time to reach $d_{s,0}$		t_{SF}	[s]	5.2	10.9	7.0
Slump flow velocity		v_{SF}	10^{-3} [m/s]	25	14	25
240 seconds at rest						
Slump flow		SF_{240}	[mm]	430	490	530
Flow time to reach $d_{s,0}$		$t_{SF,240}$	[s]	5.5	11.2	7.5
Slump flow velocity		$v_{SF,240}$	10^{-3} [m/s]	21	13	22
Variation during time at rest						
Slump flow		ΔSF	[mm]	-25	-20	-20
Flow time to reach ds,0		Δt_{SF}	[s]	0.3	0.3	0.5
Slump flow velocity		Δv_{SF}	10^{-3} [m/s]	-4	-1	-3
600 seconds at rest						
Slump flow		SF_{600}	[mm]	420	480	515
Flow time to reach $d_{s,0}$		$t_{SF,600}$	[s]	5.7	11.5	7.7
Slump flow velocity		$v_{SF,600}$	10^{-3} [m/s]	19	12	20
Variation during time at rest						
Slump flow		ΔSF	[mm]	-35	-30	-35
Flow time to reach ds,0		Δt_{SF}	[s]	0.5	0.6	0.7
Slump flow velocity		Δv_{SF}	10^{-3} [m/s]	-6	-2	-5
Vane rheometer test						
Concrete age at start			[hh:mm]	01:00	01:05	00:55
	Time at rest [s]					
Static yield stress	0	τ_{0S} (0)	[Pa]	139	103	61
	30	τ_{0S} (30)	[Pa]	294	565	281
	60	τ_{0S} (60)	[Pa]	350	668	341
	120	τ_{0S} (120)	[Pa]	435	875	409
	240	τ_{0S} (240)	[Pa]	549	1110	509
	600	$\tau 0S$ (600)	[Pa]	747	1463	707
Yield stress increase (30 - 240 s)		A_{thix}(30-240)	[Pa/s]	1.2	2.6	1.1

Table 23: Thixotropic concrete behavior – CONT.

Thixotropy					
			Batch 1	**Batch 2**	**Batch 3**
L-Box test					
Concrete age at start		[hh:mm]	01:10	01:15	01:05
0 seconds at rest (initial values)					
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.	4.9	3.0
Filling height at end of L-Box	h_0	[mm]	n.v.	60	70
Time to end of flowing	$t_{final,0}$	[s]	11.5	n.v.	n.v.
Maximum flow distance	$d_{final,0}$	[mm]	580	n.v.	n.v.
240 seconds at rest					
Flow time until end of L-Box	$t_{End,600}$	[s]	n.v.	5.8	3.4
Filling height at end of L-Box	h_{600}	[mm]	n.v.	40	55
Time to end of flowing	$t_{final,600}$	[s]	13.0	n.v.	n.v.
Maximum flow distance	$d_{final,600}$	[mm]	520	n.v.	n.v.
Variation during time at rest					
Flow time until end of L-Box	Δt_{End}	[s]	n.v.	0.9	0.4
Filling height at end of L-Box	Δh	[mm]	n.v.	-20	-15
Time to end of flowing	Δt_{final}	[s]	1.5	n.v.	n.v.
Maximum flow distance	Δd_{final}	[mm]	-60	n.v.	n.v.

The three tested concrete batches showed a high thixotropy. This can be seen by the high values for the A_{thix}(30-240), **Table 19**. Besides A_{thix}(30-240), the slump flow showed a decrease of up to 25 mm (slump flow) during 4 minutes at rest, **Table 19**. In contrast, the L-Box test did not show the pronounced thixotropic structuration as to be seen in the very slight changes in flow time and filling height for Batches 2 and 3 after 600 s at rest.

A pronounced workability loss of the concrete was observed. Already after two hours of rest, the concrete showed no more flowability. It retained its shape after lifting the slump flow cone and remained in the vertical compartment of the L-Box after lifting the lock. Even after remixing the concrete (corresponding to the usual flow retention test) the flow diameter in the slump flow test was only 25 cm.

Table 24: Flow retention behavior

Flow retention					
			Batch 1	**Batch 2**	**Batch 3**
Slump flow test					
Concrete age at start		[hh:mm]	00:50	00:55	00:45
0 hours at rest (initial values)					
Slump flow	SF	[mm]	455	510	550
Flow time to reach ds,0	t_{SF}	[s]	5.2	10.9	7.0
Slump flow velocity	v_{SF}	10^{-3} [m/s]	25	14	25
Slump	S	[mm]	250	255	255
VSI	VSI	[-]	0	0	0
2 hours at rest					
Slump flow	SF_{2h}	[mm]	200*	200*	200*,**
Flow time to reach ds,0	$t_{SF,2h}$	[s]	n.v.*	n.v.*	n.v.*,**
Slump flow velocity	$v_{SF,2h}$	10^{-3} [m/s]	n.v.*	n.v.*	n.v.*,**
Slump	S_{2h}	[mm]	300*	300*	300*,**
VSI	VSI_{2h}	[-]	0	0	0
Vane rheometer test					
Concrete age at start		[hh:mm]	01:00	01:05	00:55
0 hours at rest (initial values)					
Dynamic yield stress	τ_{0D}	[Pa]	139	103	61
Plastic viscosity	η_{pl}	[Pas]	29.0	39.0	29.0
2 hours at rest					
Dynamic yield stress	$\tau_{0D,2h}$	[Pa]	353	287	267
Plastic viscosity	$\eta_{pl,2h}$	[Pas]	55.6	58.2	50.4
L-Box test					
Concrete age at start		[hh:mm]	01:10	01:15	01:05
0 hours at rest (initial values)					
Flow time until end of L-Box	t_{End}	[s]	n.v.	4.9	3.0
Filling height at end of L-Box	h	[mm]	n.v.	60	70
Time to end of flowing	t_{final}	[s]	11.5	n.v.	n.v.
Maximum flow distance	d_{final}	[mm]	580	n.v.	n.v.
2 hours at rest					
Flow time until end of L-Box	$t_{End,2h}$	[s]	n.v.*	n.v.*	n.v.*,**
Filling height at end of L-Box	h_{2h}	[mm]	n.v.*	n.v.*	n.v.*,**
Time to end of flowing	$t_{final,2h}$	[s]	n.v.*	n.v.*	n.v.*,**
Maximum flow distance	$d_{final,2h}$	[mm]	n.v.*	n.v.*	n.v.*,**

* no more flow behavior
** no more flow behavior, even after remixing the concrete before testing

3.3.6.4 Inspection after excavation

There is no information available regarding any visual inspection after excavation. However, there is also no information about any defects nor has an excessive amount of anomalies been reported. Thus it is assumed that the tested concrete led to a positive result with regard to the filling of the excavation, and it was appropriate for the execution process applied and the structural design in place.

3.3.7 D-Wall – Producer V

3.3.7.1 General information on the construction site

Concrete testing for Producer V was carried out on July 27th and 28th, 2016 in France. The aim of the construction site was to build up a station box for a future subway by the use of D-Wall elements, Figure 14.

Figure 14: Construction site for a new station box for a future subway

It should be noted that there was no concrete placement in the D-Wall panels during our stay in Nice. However, an extra batch of each of the two concrete types to be investigated was prepared and delivered to the construction site for testing of initial dynamic and thixotropic properties as well as flow retention behavior. The duration of the delivery, climatic conditions as well as concrete consistency at arrival on site were comparable to the conditions during regular concrete delivery for the construction of the D-Wall panels. It is therefore assumed that the results, obtained for the fresh concrete properties, were representative for the concrete behavior during regular casting.

3.3.7.2 Concrete details

Two concretes were tested. The first one (testing on July 27th) was a low strength concrete, to be used to watertight the D-Wall excavation and to avoid collapses during the excavation process. It was designed for a cylinder compressive strength of 10 MPa and for a slump value of 21±3 cm (slump consistency class S4 – S5) on arrival on the construction site. Since pouring of this special concrete was only to a depth of 4 m, a good rheology was only required for a short duration after arrival on the construction site. In addition to that, the water retention ability of the concrete (filtration test) was not of major interest.

The second concrete (tested on July 28th) was to construct the D-Wall panels. The panels were planned up to a maximum depth of 50 m. The concrete was designed for a cylinder compressive strength of 35 MPa and for a slump value of 21±3 cm (slump consistency class S4 – S5) on arrival at the construction site.

Table 25: Concrete details of Producer V - low strength concrete C10

Mix design	
	Amount [kg/m³]
Cement CEM III/A 42.5 N LH/SR	
Water	
Sand 0/4 mm	
Gravel 4/20 mm (crushed)	
Superplasticizer	

Characteristic values	
w/c =	
Designated consistency class:	S4
Designated cylinder compressive strength:	10 MPa

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Table 26: Concrete details of Producer V - tremie concrete C35

Mix design	
	Amount [kg/m³]
Cement CEM III/B 42.5 N SR-PM	380
Fly ash	80
Water	188
Sand 0/4 mm	820
Gravel 6/22 mm (crushed)	920
Superplasticizer	3.01
Retarder	0.73

Characteristic values	
w/c =	0.40
w/(c+0.7f) =	0.43
Designated consistency class:	S4
Designated cylinder compressive strength:	35 MPa

3.3.7.3 Fresh concrete testing

Fresh concrete testing started around 50 minutes (C10) and 60 minutes (C35) after mixing in the plant, see Table 23.

Table 27: Concrete delivery times

General Information		
	C10	**C35**
	[hh:mm]	[hh:mm]
Time of concrete mixing at the plant:	15:10	11:10
Start of testing at the concrete plant:	16:00	12:10
Concrete age at start of testing:	00:50	01:00

The C10 concrete showed a good workability at arrival on construction site. The measured slump value was as per the design and the viscosity was moderate. On the other side, it was conspicuous that the concrete showed only a low flow distance (about 20 cm) in the horizontal compartment of the L-Box. Although high water retention ability was not necessary for this concrete, the Bauer filtration test was performed. The concrete showed high filtration tendencies, the filtration loss in the Bauer filtration press was about 35 ml. **Table 24** shows the measured values regarding the initial dynamic testing.

Table 28: Initial dynamic concrete behavior, mix design C10

Initial dynamic behavior			
			Batch 1
Flow table test			
Concrete age at start		[hh:mm]	01:00
Spread flow (without hit)	a_0	[mm]	420
Spread (with15 hits)	a	[mm]	595
Slump flow test			
Concrete age at start		[hh:mm]	01:10
Slump flow	SF	[mm]	400
Flow time to reach ds,0	t_{SF}	[s]	3.3
Slump flow velocity	v_{SF}	10^{-3} [m/s]	30
Slump	S	[mm]	235
VSI	VSI_0	[-]	0
Vane rheometer test			
Concrete age at start		[hh:mm]	01:20
Dynamic yield stress	τ_{0D}	[Pa]	187
Plastic viscosity	η_{pl}	[Pas]	23
L-Box test			
Concrete age at start		[hh:mm]	01:30
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.
Filling height at end of L-Box	h_0	[mm]	n.v.
Time to end of flowing	$t_{final,0}$	[s]	8
Maximum flow distance	$d_{final,0}$	[mm]	200
Bauer filtration test			
Concrete age at start		[hh:mm]	01:40
Filtration loss	$t_{End,0}$	[ml]	34
Filter Cake thickness	h_0	[mm]	16.5

The C35 concrete showed a consistency (slump value) as per the design on arrival at the construction site. Furthermore, the concrete exhibited a high viscosity, quantified in the dynamic vane rheometer measurements as well as demonstrated by low values of the flow velocity during testing, i.e. the time to reach the maximum flow distance in the horizontal compartment of the L-Box.

Table 29: Initial dynamic concrete behavior, mix design C35

Initial dynamic behavior			
			Batch 1
Flow table test			
Concrete age at start		[hh:mm]	01:10
Spread flow (without hit)	a_0	[mm]	350
Spread (with15 hits)	a	[mm]	520
Slump flow test			
Concrete age at start		[hh:mm]	01:20
Slump flow	SF	[mm]	375
Flow time to reach ds,0	t_{SF}	[s]	7.9
Slump flow velocity	v_{SF}	10^{-3} [m/s]	11
Slump	S	[mm]	235
VSI	VSI_0	[-]	0
Vane rheometer test			
Concrete age at start		[hh:mm]	01:30
Dynamic yield stress	τ_{0D}	[Pa]	273
Plastic viscosity	η_{pl}	[Pas]	55.0
L-Box test			
Concrete age at start		[hh:mm]	01:40
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.
Filling height at end of L-Box	h_0	[mm]	n.v.
Time to end of flowing	$t_{final,0}$	[s]	12.9
Maximum flow distance	$d_{final,0}$	[mm]	490
Bauer filtration test			
Concrete age at start		[hh:mm]	01:50
Filtration loss	$t_{End,0}$	[ml]	10
Filter Cake thickness	h_0	[mm]	50

The C10 concrete showed a very low thixotropy – only a slight increase of the static yield stress could be measured in the vane rheometer for an increasing time at rest. **Table 26** shows the measured values for the thixotropic behavior of the C10 concrete batch.

Table 30: Thixotropic concrete behavior, mix design C10

Thixotropy				
				Batch 1
Slump flow test				
Concrete age at start			[hh:mm]	01:10
0 seconds at rest (initial values)				
Slump flow		SF	[mm]	400
Flow time to reach $d_{s,0}$		t_{SF}	[s]	3.3
Slump flow velocity		v_{SF}	10^{-3} [m/s]	30
240 seconds at rest				
Slump flow		SF_{240}	[mm]	375
Flow time to reach $d_{s,0}$		$t_{SF,240}$	[s]	3.5
Slump flow velocity		$v_{SF,240}$	10^{-3} [m/s]	28
Variation during time at rest				
Slump flow		ΔSF	[mm]	-25
Flow time to reach ds,0		Δt_{SF}	[s]	0.2
Slump flow velocity		Δv_{SF}	10^{-3} [m/s]	-2
600 seconds at rest				
Slump flow		SF_{600}	[mm]	360
Flow time to reach $d_{s,0}$		$t_{SF,600}$	[s]	3.5
Slump flow velocity		$v_{SF,600}$	10^{-3} [m/s]	23
Variation during time at rest				
Slump flow		ΔSF	[mm]	-40
Flow time to reach ds,0		Δt_{SF}	[s]	0.2
Slump flow velocity		Δv_{SF}	10^{-3} [m/s]	-7
Vane rheometer test				
Concrete age at start			[hh:mm]	01:20
	Time at rest [s]			
Static yield stress	0	τ_{0S} (0)	[Pa]	187
	30	τ_{0S} (30)	[Pa]	1022
	60	τ_{0S} (60)	[Pa]	1077
	120	τ_{0S} (120)	[Pa]	1133
	240	τ_{0S} (240)	[Pa]	1192
	600	τ_{0S} (600)	[Pa]	1491
Yield stress increase (30 - 240 s)		A_{thix}(30-240)	[Pa/s]	0.8

Table 31: Thixotropic concrete behavior, mix design C10 – CONT.

Thixotropy			
			Batch 1
L-Box test			
Concrete age at start		[hh:mm]	01:30
0 seconds at rest (initial values)			
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.
Filling height at end of L-Box	h_0	[mm]	n.v.
Time to end of flowing	$t_{final,0}$	[s]	8
Maximum flow distance	$d_{final,0}$	[mm]	200
600 seconds at rest			
Flow time until end of L-Box	$t_{End,600}$	[s]	n.v.
Filling height at end of L-Box	h_{600}	[mm]	n.v.
Time to end of flowing	$t_{final,600}$	[s]	9
Maximum flow distance	$d_{final,600}$	[mm]	160
Variation during time at rest			
Flow time until end of L-Box	Δt_{End}	[s]	n.v.
Filling height at end of L-Box	Δh	[mm]	n.v.
Time to end of flowing	Δt_{final}	[s]	1
Maximum flow distance	Δd_{final}	[mm]	-40

The C35 concrete showed a strong increase in static yield stress in the static rheometer test, representing its high thixotropy. The same trend can be seen for the L-Box test, were the flow distance significantly decreased after 600 s at rest. In contrast, the decrease of the slump flow as an effect of time at rest was not that pronounced. **Table 27** shows the measured values for the thixotropic behavior of the C35 concrete batch.

Table 32: Thixotropic concrete behavior, mix design C35

<table>
<tr><th colspan="5">Thixotropy</th></tr>
<tr><td colspan="2"></td><td></td><td></td><td>Batch 1</td></tr>
<tr><td colspan="5">Slump flow test</td></tr>
<tr><td colspan="2">Concrete age at start</td><td></td><td>[hh:mm]</td><td>01:20</td></tr>
<tr><td colspan="5"><i>0 seconds at rest (initial values)</i></td></tr>
<tr><td colspan="2">Slump flow</td><td>SF</td><td>[mm]</td><td>375</td></tr>
<tr><td colspan="2">Flow time to reach $d_{s,0}$</td><td>t_{SF}</td><td>[s]</td><td>7.9</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>v_{SF}</td><td>10^{-3} [m/s]</td><td>11</td></tr>
<tr><td colspan="5"><i>240 seconds at rest</i></td></tr>
<tr><td colspan="2">Slump flow</td><td>SF_{240}</td><td>[mm]</td><td>370</td></tr>
<tr><td colspan="2">Flow time to reach $d_{s,0}$</td><td>$t_{SF,240}$</td><td>[s]</td><td>8.1</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>$v_{SF,240}$</td><td>10^{-3} [m/s]</td><td>11</td></tr>
<tr><td colspan="5"><i>Variation during time at rest</i></td></tr>
<tr><td colspan="2">Slump flow</td><td>ΔSF</td><td>[mm]</td><td>-5</td></tr>
<tr><td colspan="2">Flow time to reach ds,0</td><td>Δt_{SF}</td><td>[s]</td><td>0.2</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>Δv_{SF}</td><td>10^{-3} [m/s]</td><td>0</td></tr>
<tr><td colspan="5"><i>600 seconds at rest</i></td></tr>
<tr><td colspan="2">Slump flow</td><td>SF_{600}</td><td>[mm]</td><td>360</td></tr>
<tr><td colspan="2">Flow time to reach $d_{s,0}$</td><td>$t_{SF,600}$</td><td>[s]</td><td>8.0</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>$v_{SF,600}$</td><td>10^{-3} [m/s]</td><td>10</td></tr>
<tr><td colspan="5"><i>Variation during time at rest</i></td></tr>
<tr><td colspan="2">Slump flow</td><td>ΔSF</td><td>[mm]</td><td>-15</td></tr>
<tr><td colspan="2">Flow time to reach ds,0</td><td>Δt_{SF}</td><td>[s]</td><td>0.1</td></tr>
<tr><td colspan="2">Slump flow velocity</td><td>Δv_{SF}</td><td>10^{-3} [m/s]</td><td>-1</td></tr>
<tr><td colspan="5">Vane rheometer test</td></tr>
<tr><td colspan="2">Concrete age at start</td><td></td><td>[hh:mm]</td><td>01:30</td></tr>
<tr><td></td><td>Time at rest [s]</td><td></td><td></td><td></td></tr>
<tr><td rowspan="6">Static yield stress</td><td>0</td><td>τ_{0S} (0)</td><td>[Pa]</td><td>273</td></tr>
<tr><td>30</td><td>τ_{0S} (30)</td><td>[Pa]</td><td>2222</td></tr>
<tr><td>60</td><td>τ_{0S} (60)</td><td>[Pa]</td><td>2444</td></tr>
<tr><td>120</td><td>τ_{0S} (120)</td><td>[Pa]</td><td>2623</td></tr>
<tr><td>240</td><td>τ_{0S} (240)</td><td>[Pa]</td><td>3033</td></tr>
<tr><td>600</td><td>τ_{0S} <i>(600)</i></td><td>[Pa]</td><td>3796</td></tr>
<tr><td colspan="2">Yield stress increase (30 - 240 s)</td><td>A_{thix}(30-240)</td><td>[Pa/s]</td><td>3.8</td></tr>
</table>

Table 33: Thixotropic concrete behavior, mix design C35 - CONT

Thixotropy			
			Batch 1
L-Box test			
Concrete age at start		[hh:mm]	01:40
0 seconds at rest (initial values)			
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.
Filling height at end of L-Box	h_0	[mm]	n.v.
Time to end of flowing	$t_{final,0}$	[s]	12.9
Maximum flow distance	$d_{final,0}$	[mm]	490
600 seconds at rest			
Flow time until end of L-Box	$t_{End,600}$	[s]	n.v.
Filling height at end of L-Box	h_{600}	[mm]	n.v.
Time to end of flowing	$t_{final,600}$	[s]	14.7
Maximum flow distance	$d_{final,600}$	[mm]	280
Variation during time at rest			
Flow time until end of L-Box	Δt_{End}	[s]	n.v.
Filling height at end of L-Box	Δh	[mm]	n.v.
Time to end of flowing	Δt_{final}	[s]	1.8
Maximum flow distance	Δd_{final}	[mm]	-210

The flow retention behavior was only tested for the C35 concrete since the C10 concrete was not designed for time-consuming placement (maximum depth of 4 m). After 2 hours at rest, the C35 concrete was of stiff consistency and retained its shape after lifting the slump flow cone or the lock in the L-Box. Even the rheometer wasn’t able to do any further measurement. Possible causes for this strong stiffening are the long transportation times of the concrete from the concrete plant to the construction site (about 1 hour) and thus the increased concrete age for the testing after two hours at rest (about 3 hours) in combination with the high fresh concrete temperature (27°C at delivery) and the high ambient temperature (about 30°C).

3.3.7.4 Inspection after excavation

There is no information available regarding any visual inspection after excavation. However, there is also no information about any defects nor have an excessive amount of anomalies been reported. Thus it is assumed that the tested concrete led to a positive result with regard to the filling of the excavation, and it was appropriate for the execution process applied and the structural design in place.

3.3.8 Bored piles – Producer VI

3.3.8.1 General information on the construction site

This concrete testing on the construction site was carried out on November 29th, 2016 in Germany. The aim of this construction site is to build a new lock, Figure 15. Producer VI constructed bored piles for this purpose. The bored piles had a diameter of 1.2 m and a maximum depth of about 13 m. The pouring was done underwater.

Figure 15: Bored piles for a new lock

3.3.8.2 Concrete details

The concrete was designed for a cylinder compressive strength of 30 MPa and for a spread value of 560 - 620 mm (consistency class F5). A retarding agent was used for this concrete in order to get a retardation of the cement hydration of about 2 hours. Details of the mixture proportions can be taken from **Table 28**.

Table 34: Concrete details of Producer VI

Mix design	
	Amount [kg/m^3]
Cement CEM III/B 42.5 N SR-PM	330
Fly ash	100
Water	195
Sand 0/2 mm	633
Gravel 2/16 mm (rounded)	1034
Superplasticizer	1.65
Retarder	0.66

Characteristic values	
w/c =	0.59
w/(c+0.7f) =	0.49
Designated consistency class:	Spread: 560 - 620 mm (F5)
Designated cylinder compressive strength:	30 MPa

3.3.8.3 Fresh concrete testing

Fresh concrete testing started around 40 minutes after mixing in the plant, see **Table 29**.

Table 35: Concrete delivery times

General Information	
	Batch 1
	[hh:mm]
Time of concrete mixing at the plant:	9:00
Start of testing at the concrete plant:	09:40
Concrete age at start of testing:	00:40

Due to the low ambient temperatures (-5°C), concrete testing on the construction site was carried out in a heated container at around 20°C. Thus the temperature conditions were roughly comparable to the temperatures inside the bored pile during concrete pouring.

One batch of the concrete was fully tested regarding its initial dynamic and thixotropic properties as well as its flow retention behavior. At the same time, the German Federal Waterways Engineering and Research Institute tested the segregation and bleeding tendencies of that concrete batch.

Table 30 displays the test results regarding the initial dynamic concrete behavior. The concrete exhibited a spread value of 620 mm at arrival on the construction site (upper limit of F5 – as per design). The viscosity of the concrete was intermediate, compared to the concretes used on the previous construction sites, demonstrated by intermediate values for the flow time to reach the end of the horizontal section of the L-Box. Furthermore, the concrete showed a pronounced filtration loss in the Bauer filtration test.

Table 36: Initial dynamic concrete behavior

Initial dynamic behavior			
			Batch 1
Flow table test			
Concrete age at start		[hh:mm]	00:50
Spread flow (without hit)	a_0	[mm]	410
Spread (with15 hits)	a	[mm]	620
Slump flow test			
Concrete age at start		[hh:mm]	01:00
Slump flow	SF	[mm]	500
Flow time to reach ds,0	t_{SF}	[s]	5.8
Slump flow velocity	v_{SF}	10^{-3} [m/s]	26
Slump	S	[mm]	260
VSI	VSI_0	[-]	0
Vane rheometer test			
Concrete age at start		[hh:mm]	01:10
Dynamic yield stress	τ_{0D}	[Pa]	130
Plastic viscosity	η_{pl}	[Pas]	30.2
L-Box test			
Concrete age at start		[hh:mm]	01:20
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.
Filling height at end of L-Box	h_0	[mm]	n.v.
Time to end of flowing	$t_{final,0}$	[s]	6.0
Maximum flow distance	$d_{final,0}$	[mm]	600
Bauer filtration test			
Concrete age at start		[hh:mm]	01:50
Filtration loss	$t_{End,0}$	[ml]	36
Filter Cake thickness	h_0	[mm]	125

Figure 16 and Figure 17 summarize the results on the bleeding and segregation behavior, collected by the German Federal Waterways Engineering and Research Institute.

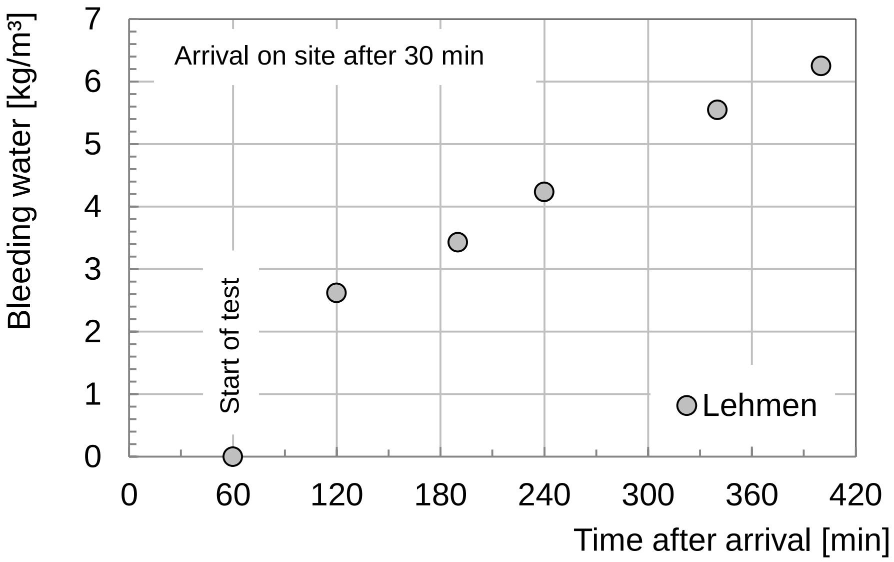

Figure 16: Bleed behavior of the concrete (results collected by the German Federal Waterways Engineering and Research Institute)

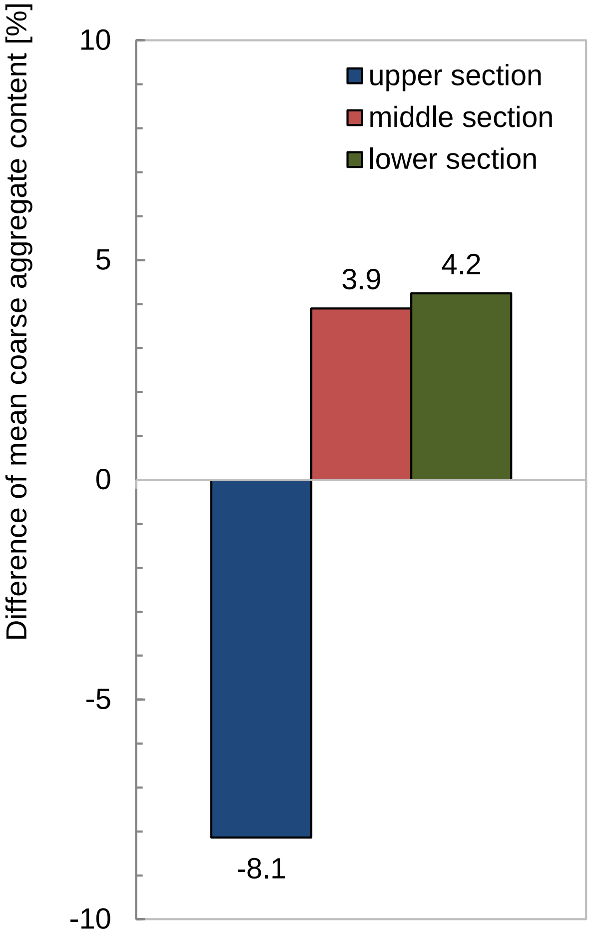

Figure 17: Segregation behavior of the concrete (results collected by the German Federal Waterways Engineering and Research Institute)

The concrete shows a moderate thixotropic structural build up. This can be seen in the moderate decrease of the slump flow during time at rest or the moderate value for A_{thix}(30-240), see **Table 31**.

Table 37: Thixotropic concrete behavior

Thixotropy				
				Batch 1
Slump flow test				
Concrete age at start			[hh:mm]	01:00
0 seconds at rest (initial values)				
Slump flow		SF	[mm]	500
Flow time to reach $d_{s,0}$		t_{SF}	[s]	5.8
Slump flow velocity		v_{SF}	10^{-3} [m/s]	26
240 seconds at rest				
Slump flow		SF_{240}	[mm]	485
Flow time to reach $d_{s,0}$		$t_{SF,240}$	[s]	6.9
Slump flow velocity		$v_{SF,240}$	10^{-3} [m/s]	21
Variation during time at rest				
Slump flow		ΔSF	[mm]	-15
Flow time to reach ds,0		Δt_{SF}	[s]	1.1
Slump flow velocity		Δv_{SF}	10^{-3} [m/s]	-5
600 seconds at rest				
Slump flow		SF_{600}	[mm]	460
Flow time to reach $d_{s,0}$		$t_{SF,600}$	[s]	8.3
Slump flow velocity		$v_{SF,600}$	10^{-3} [m/s]	16
Variation during time at rest				
Slump flow		ΔSF	[mm]	-40
Flow time to reach ds,0		Δt_{SF}	[s]	2.5
Slump flow velocity		Δv_{SF}	10^{-3} [m/s]	-10
Vane rheometer test				
Concrete age at start			[hh:mm]	01:10
	Time at rest [s]			
Static yield stress	0	τ_{0S} (0)	[Pa]	130
	30	τ_{0S} (30)	[Pa]	716
	60	τ_{0S} (60)	[Pa]	740
	120	τ_{0S} (120)	[Pa]	764
	240	τ_{0S} (240)	[Pa]	819
	600	τ_{0S} (600)	[Pa]	928
Yield stress increase (30 - 240 s)		A_{thix}(30-240)	[Pa/s]	0.49

Table 38: Thixotropic concrete behavior – CONT.

Thixotropy			
			Batch 1
L-Box test			
Concrete age at start		[hh:mm]	01:20
0 seconds at rest (initial values)			
Flow time until end of L-Box	$t_{End,0}$	[s]	n.v.
Filling height at end of L-Box	h_0	[mm]	n.v.
Time to end of flowing	$t_{final,0}$	[s]	6.0
Maximum flow distance	$d_{final,0}$	[mm]	600
600 seconds at rest			
Flow time until end of L-Box	$t_{End,600}$	[s]	n.v.
Filling height at end of L-Box	h_{600}	[mm]	n.v.
Time to end of flowing	$t_{final,600}$	[s]	6.5
Maximum flow distance	$d_{final,600}$	[mm]	560
Variation during time at rest			
Flow time until end of L-Box	Δt_{End}	[s]	n.v.
Filling height at end of L-Box	Δh	[mm]	n.v.
Time to end of flowing	Δt_{final}	[s]	0.5
Maximum flow distance	Δd_{final}	[mm]	-40

The flow retention ability of the concrete was rather good, shown by moderate changes in the slump flow diameter and the dynamic yield stress after 2 hours at rest, compared to the initial values at arrival on construction site, **Table 32**.

Table 39: Flow retention behavior

Flow retention			
			Batch 1
Slump flow test			
Concrete age at start		[hh:mm]	01:00
0 hours at rest (initial values)			
Slump flow	SF	[mm]	500
Flow time to reach ds,0	t_{SF}	[s]	5.8
Slump flow velocity	v_{SF}	10^{-3} [m/s]	26
Slump	S	[mm]	260
VSI	VSI	[-]	0
2 hours at rest			
Slump flow	SF_{2h}	[mm]	330
Flow time to reach ds,0	$t_{SF,2h}$	[s]	5.6
Slump flow velocity	$v_{SF,2h}$	10^{-3} [m/s]	12
Slump	S_{2h}	[mm]	n.v.
VSI	VSI_{2h}	[-]	0
3.5 hours at rest			
Slump flow	$SF_{3.5h}$	[mm]	200*
Flow time to reach ds,0	$t_{SF,3.5h}$	[s]	n.v.*
Slump flow velocity	$v_{SF,3.5h}$	10^{-3} [m/s]	n.v.*
Slump	$S_{3.5h}$	[mm]	300*
VSI	$VSI_{3.5h}$	[-]	0
Vane rheometer test			
Concrete age at start		[hh:mm]	01:10
0 hours at rest (initial values)			
Dynamic yield stress	τ_{0D}	[Pa]	130
Plastic viscosity	η_{pl}	[Pas]	30.2
2 hours at rest			
Dynamic yield stress	$\tau_{0D,2h}$	[Pa]	386
Plastic viscosity	$\eta_{pl,2h}$	[Pas]	47.2
3.5 hours at rest			
Dynamic yield stress	$\tau_{0D,3.5h}$	[Pa]	569
Plastic viscosity	$\eta_{pl,3.5h}$	[Pas]	67.1

Table 40: Flow retention behavior - CONT.

Flow retention			
			Batch 1
L-Box test			
Concrete age at start		[hh:mm]	01:30
0 hours at rest (initial values)			
Flow time until end of L-Box	t_{End}	[s]	n.v.
Filling height at end of L-Box	h	[mm]	n.v.
Time to end of flowing	t_{final}	[s]	6.0
Maximum flow distance	d_{final}	[mm]	600
2 hours at rest			
Flow time until end of L-Box	$t_{End,2h}$	[s]	n.v.
Filling height at end of L-Box	h_{2h}	[mm]	n.v.
Time to end of flowing	$t_{final,2h}$	[s]	8.9
Maximum flow distance	$d_{final,2h}$	[mm]	300
3.5 hours at rest			
Flow time until end of L-Box	$t_{End,3.5h}$	[s]	n.v.*
Filling height at end of L-Box	$h_{3.5h}$	[mm]	n.v.*
Time to end of flowing	$t_{final,3.5h}$	[s]	n.v.*
Maximum flow distance	$d_{final,3.5h}$	[mm]	n.v.*

* no more flow behavior

3.3.8.4 Inspection after excavation

There is no information available regarding any visual inspection after excavation. However, there is also no information about any defects nor has an excessive amount of anomalies been reported. Thus it is assumed that the tested concrete led to a positive result with regard to the filling of the excavation, and it was appropriate for the execution process applied and the structural design in place.

3.4 Test Program on American Construction Sites

3.4.1 General procedure

This test program differs from the European one in one major point: whereas in Europe testing of the fresh concrete properties was carried out by the scientific staff directly on the construction site, the US work program is subdivided in three parts, 1) performance of a reduced test program on the construction sites (done by the several Producers), 2) performance of an extended test program with these concrete mixtures (original raw materials were shipped to Missouri S&T) in the lab by the scientific staff and 3) comparison between the lab and the field results.

3.4.2 Mixture compositions and preparation of concretes

“For all mixtures, the representative materials were shipped to Missouri S&T and were employed for the reproduction of the concrete mix designs. In total, six mixtures were evaluated. The mixtures from the different producers are named A to F, to avoid revealing the identity of the suppliers. This report contains three main sections. In the first section, the mix designs of the different mixtures are listed. It should be noted that the HRWRA quantity was adjusted for all mix designs to achieve the flowability of the mixtures, as reported in the field. Differences in mixing energy in the lab compared to the field could induce some non-desirable effects (too stiff or segregating mixtures), if an identical amount of HRWRA was added. The second section of this report contains the laboratory test results of mixtures A to F, showing interactions between different parameters. In the third section, the lab data are compared to field data.” (Feys et al., 2018)

3.4.3 Test program on construction site

See (Feys et al., 2018)

3.4.4 Test program in the laboratory

See (Feys et al., 2018)

3.5 Results from the American Construction Sites

A detailed description of the results of the US experimental program can be taken from (Feys et al., 2018). The summary below of Feys Report describes the major findings.

1. Good **correlations between dynamic yield stress and slump flow** were obtained, comparable to the European data.
2. A good **correlation** between **viscosity and slump flow speed**, calculated as 300/T50 (mm/s), was obtained. However, for the slump flow speed data calculated based on T_{final}, no correlation with the viscosity was found.

   Note of the author: Calculation of T_{final} in the US experimental program was done in a different way from that done in the European program. Calculation of T_{final} by the "European way" using the US raw data leads to a sufficient correlation between concrete viscosity and T_{final}
3. The **retention of yield stress** over time is **well related to the slump flow retention** and the L-box H2/H1 retention. Also, the mixtures in the lab follow similar trends as the mixtures in the field concerning slump flow retention.
4. The viscosity has been found to vary minimally over time, as expected.
5. Static yield stress measurements with the **ICAR rheometer in a 10 min time span shows** substantial differences in **thixotropic behavior** of the mixtures. The **portable vane test**, executed **over a 60 min time period**, shows a **similar capacity** to distinguish between the mixtures.
6. Using the **difference in slump flow or L-box filling ratio**, **taken from an initial and a delayed measurement, does not deliver adequate indicators for thixotropic build-up** at rest. Hence, it was suggested to remove these measurements.
7. Static stability results show that all mixtures are stable (column segregation value < 15%). The lab results are in line with the field data.
8. The total % bleeding of the mixtures evaluated in the lab corresponds well to the values reported in the field. Bleeding rate data was also derived.
9. The results from the Bauer filter press in the lab show a similar behavior as in the field, although the lab results are systematically higher.

➔ Based on these results, the following recommendations were developed for test methods for deep foundation concrete:

  - For dynamic yield stress, slump flow and L-box are in good agreement. Hence, one test method can be executed to evaluate the filling ability of the mixture and its evolution with time.
  - The static yield stress tests have revealed significant differences in thixotropic behavior. As such, either a rheometer static yield stress test, or a portable vane static yield stress test is recommended to be executed in the field to monitor the structural build-up of the material at rest. Attempts to derive thixotropy from a delayed slump flow or delayed L-box test were unsuccessful.
  - Stability needs to be verified separately, as this cannot be captured by means of the other tests. Whether only one test, or three tests (static segregation, bleeding, or forced bleeding (Bauer)) need to be executed is unclear up to date, but all tests capture differences between the concrete mix designs.

4. WP 2: Effect of concrete composition on rheology, workability and stability - laboratory tests

4.1 Raw materials

To describe for the final report

4.2 Planned mixture variations

Figure 26 gives an overview on the planned variations of the current R&D project. Details information on the mixture compositions under investigation can be found in the following sections.

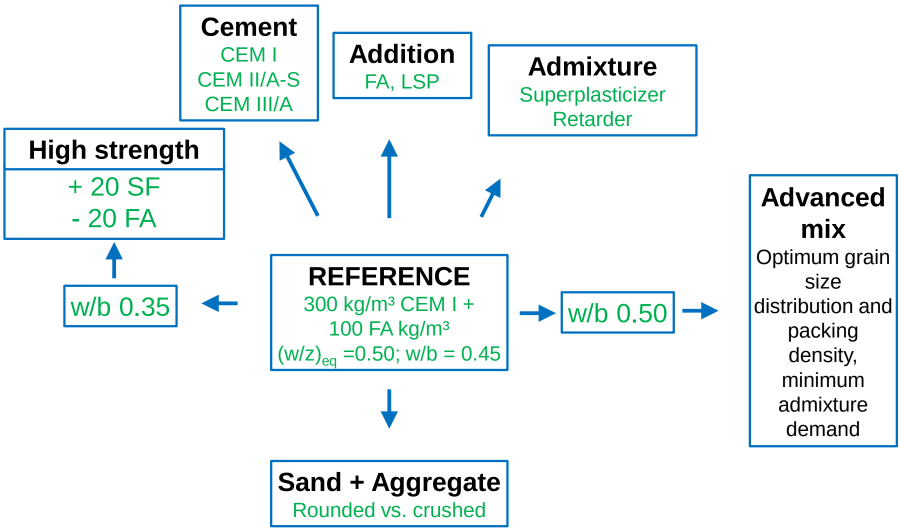

Figure 18: Planned variations in the R&D project

4.3 Mix 1 – Provisional concrete mix

The provisional concrete mix corresponds to a conventional concrete mix design for bored piles for deep foundations, especially for the secondary, reinforced bored piles being poured by means of the tremie process.

Table 41: Mixture composition of provisional concrete

Material	Producer	[kg/m^3]	[kg/dm^3]	[dm^3/m^3]
[-]	[-]	[mm]	[mm]	[mm]
1	2	3	4	5
Ordinary Portland Cement “CEM I 42.5 R”	Schwenk Zement KG	300	3.1	96.8
Fly Ash “Safament”	VKN Saar GmbH	100	2.4	41.7
Water	-	180	1.0	180
Superplasticizer “Master Glenium 51”	BASF	2.3	1.05	2.2

Sand 0/4 mm	Glück GmbH	880	2.75	320
Gravel 4/8 mm	Glück GmbH	351	2.76	127
Gravel 8/16 mm	Glück GmbH	643	2.73	235

The provisional concrete was used to examine the feasibility of the planned test program. In particular, it was tested whether the time schedule of the test program could be kept to. Furthermore, it was checked whether the tests for the planned fresh concrete would be suitable for the soft to flowable consistency of the concretes for deep foundations. For that reason, the provisional concrete was produced a number of times. The consistency of the concrete was systematically varied by an adjustment of the content of the superplasticizer in order to cover the full range of consistency typically used for diaphragm walls and bored piles in deep foundations.

It was found that the proposed fresh concrete test setup was well suited for the assessment of the characteristics of the deep foundation concretes in the fresh state. However, depending on the consistency of the concrete, only certain values can be determined. For example, in the slump flow test, the flow time of the concrete to reach a diameter of 500 mm (t_{500}) can only be measured for mixtures with high flowability, where the final slump flow diameter (d_s) is significantly higher than 500 mm. Therefore, the time to the end of flow t_{final} instead of t_{500} was used in the further investigations. This t_{final} can be determined for all concretes, independent of their consistency (between soft and highly flowable). A second example where the consistency of the fresh concrete has also to be taken into consideration is the L-Box test. There the measured time to reach the end of the horizontal part of the L-Box t_{end} and the related height h_{end} of the concrete at this point are suitable to describe the properties of flowable concretes. In contrast, concretes with soft consistency will not reach the end of the L-Box. For these concretes, the time to the end of flow in the box t_{final} and the related maximum flow distance l_{final} are applicable parameters to describe the fresh concrete properties.

4.4 Mix 2 – Reference concrete

With regard to its material composition Mix 2 corresponds to the provisional concrete Mix 1. However, an Ordinary Portland Cement CEM I 42.5 R of HeidelbergCement was used instead of the CEM I 42.5 R of Schwenk Zement KG. The reason for that change is that HeidelbergCement is one of the sponsors of the project. HeidelbergCement provides us with a full characterization of the delivered charge of cement, e.g. chemical composition, specific surface (Blaine), water demand, particle size distribution or BET-surface. This information is of interest for the R&D project, regarding for example the interaction between the cement and the various additives (superplasticizer, retarder, air entraining agents…), typically used in deep foundation concretes, and thus the effectiveness of the single ingredients.

Furthermore, the type of superplasticizer was changed from the provisional concrete to the reference mix. This was done because the provisional concrete contained a superplasticizer with a short workability time (rather as used in precast industries). However, the superplasticizer used for the reference mix, designated BASF MasterGlenium SKY 592 is designed especially to maintain good flow retention properties. It is therefore a proven superplasticizer, representative for use in deep foundations, especially when the duration of concrete placement lasts for many hours.

As expected, the reference mix showed good workability and flow retention properties during testing in the laboratory. It is worth noting that the reference mix exhibited a significant lower thixotropy compared to the provisional mix.

4.5 Mix 3 – Variation in type of cement, CEM II

The material composition of Mix 3 corresponds to the reference concrete (Mix 2), except that the type of cement was different. A Portland Slag Cement CEM II/A-S 42.5 R was used instead of CEM I 42.5 R. Since both cements are in the delivery program of HeidelbergCement KG we are enabled to obtain a full characterization of the delivered charges of cements, see Section 2.2.

The replacement of the CEM I by the CEM II was in order to reduce the hydration heat development in the concrete which is a main issue for mass structural elements. It should be determined how this cement replacement affects the rheology of the concrete. First results showed a comparable rheological behaviour of Mix 3 regarding its initial dynamic properties. In addition to that, the use of CEM II led to a slightly decrease of the thixotropic structural built-up of the concrete during the first minutes at rest. Furthermore slightly increased bleeding tendencies were observed for the CEM II-concrete.

4.6 Mix 4 – Measurements regarding the accuracy of the thixotropy testing procedure with the vane rheometer

The reference concrete (Mix 2) was used for these tests. A retarding agent was additionally added in order to obtain the smallest possible change in the fresh concrete properties during the test period.

The aim of the tests was to answer the question asked at the R&D meeting in June 2015 in Munich. The question was whether the reversible microstructure formation in the concrete (a measure of thixotropy) is independent of the number of static yield stress measurements during one measuring cycle in the rheometer. In other words: does the slow rotation of the vane paddle during the single measurements disturb the microstructure formation at rest?

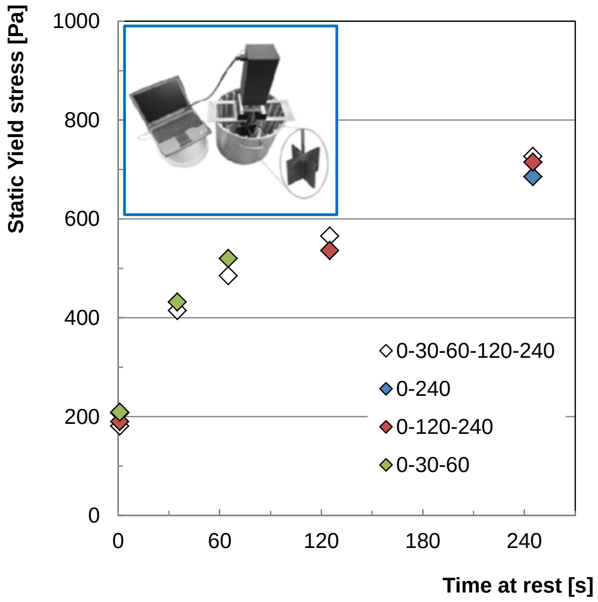

Figure 19: Static yield stress measurements on the reference concrete after different times at rest

To answer this question, four measuring cycles were examined on the same concrete. Before every measuring cycle, the concrete was stirred up in order to achieve a structural breakdown (minimum yield value at the beginning of every measuring cycle).

After that, the concrete was stored at rest and static yield stress measurements were performed after different times during the first four minutes at rest. For the static yield stress measurements, the vane paddle of the rheometer was moved for a short time (approximately 2 s) at a low rotational speed and the maximum shear stress recorded. Static shear stress measurements were carried out after 0, 30, 60, 120 and 240 seconds at rest for the 1st measuring cycle, after 0 and 240 seconds for the 2nd measuring cycle, after 0, 120 and 240 seconds for the 3rd measuring cycle and after 0, 30 and 60 seconds for the 4th measuring cycle. The results of the four measuring cycles are show in Figure 18. It was therefore demonstrated that the thixotropic microstructural build-up of the fresh concrete is independent of the number of yield stress measurements within one measuring cycle.

4.7 Mix 5 – Variation in type of cement, CEM III

The material composition of Mix 5 corresponded to the reference concrete (Mix 2), except that the type of cement was different. Blast furnace slag cement CEM III/A-S 42.5 N was used instead of CEM I 42.5 R. The replacement of the CEM I by the CEM III was a second step (after the replacement of CEM I 42.5 R by CEM II) to reduce the ordinary Portland cement (OPC) clinker content and therefore the hydration heat development of the concrete which is a main issue for mass structural elements. It should be determined how this cement replacement affects the rheology of the concrete and thus its form filling behavior.

Concrete mixes with an initial consistency, comparable to the mixes using CEM I (Mix 2) and CEM II (Mix 3) were produced. As expected, the concretes (using CEM I, CEM; II as well as CEM III) showed a comparable dynamic yield stress.

For decreasing OPC clinker contents (increasing blast furnace slag contents), a slight decrease in plastic viscosity was observed during the vane-rheometer tests. This was confirmed by slightly higher flow velocities for lower OPC clinker contents observed during the slump flow and L-Box tests, i.e. the time to reach the final slump flow diameter and the time to reach the end of the horizontal compartment of the L-Box.

The rheological measurements concerning the thixotropic structural build-up of the undisturbed concretes revealed a decrease in thixotropic behavior of the concretes with OPC clinker content, as shown by the less pronounced increase in static yield stress with time at rest. This applies for the first minutes after mixing as well as for longer times, Fig. 8 left and right.

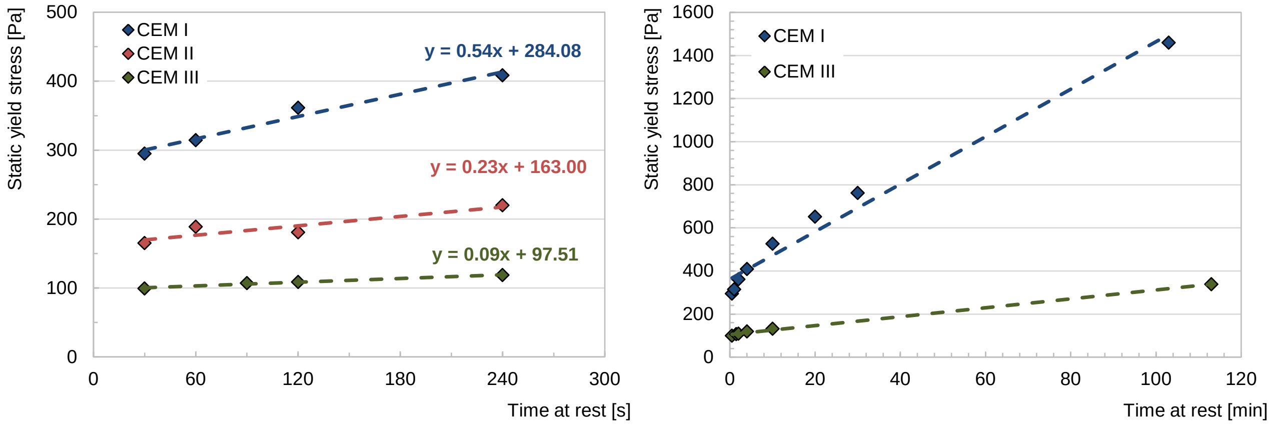

Figure 20: Increase of static yield stress of the concretes during resting time as a measure of thixotropy for the different types of cement (CEM I, CEM II, CEM III) used

Regarding the flow retention behavior, the CEM I concrete was advantageous. With decreasing OPC clinker content of the concrete, the workability loss was somewhat more pronounced.

4.8 Mix 6 – Reference concrete with consistency extender

The purpose of the test series was to determine the general effect of a consistency extender on the rheological behavior of the reference concrete. A consistency extender is an admixture which enhances the flow retention and thus prolongs the workability time of the concrete without the use of a classic retarding agent. A consistency extender “MasterSure 900” from BASF was used for the test series. The other material composition of Mix 6 corresponds to the reference concrete (Mix 2), except the superplasticizer (“SP”) content. Compared to the reference concrete, the SP content could be reduced for Mix 6 to reach a similar initial consistency. It was found that the concrete with the consistency extender led to a pronounced workability loss – the opposite of the intended effect. A reason for this behavior might be found in the reduced SP content of the concrete. The SP used for the reference concrete and the concrete with the consistency extender provided good flow retention properties of the concrete. It is therefore used, in particular, for applications with a time consuming placement process, like deep foundations. It is assumed that this special SP extends the workability time in a more efficient way than the tested consistency extender. Further research will be undertaken with another type of consistency extender in order to enable a further extension of the workability time of deep foundation concretes.

4.9 Mix 7 – Reference concrete with alternative superplasticizer (MasterEase 3000)

The purpose of the test series was to determine the effect of an alternative type of SP, on workability and rheology of deep foundation concretes. An SP named MasterEase 3000, produced and distributed by BASF was used for this purpose. The SP is a polyacryl-ether-based (PAE) instead of the typically used polycarboxylate-ether-based ones (PCE). The aim of this special SP is to significantly reduce the viscosity of the fresh concrete and thus to improve its pumping, placing and finishing process.

Except the type and content of the SP, the material composition of Mix 7 was equal to the reference concrete (Mix 2). It was found that an increased content of the alternative SP had to be used to reach an initial consistency (spread value, slump flow diameter) and dynamic yield stress, similar to that of the reference mix. On the other hand, the viscosity was reduced about 30 % compared to the reference mix. Higher values for the calculated flow velocities in the slump flow test and the L-Box test are the consequence.

In terms of the thixotropy, both mixes behaved in a similar manner. The time dependent increase of the static yield stress as a measure of the thixotropic structural development of the undisturbed concrete was almost equal, see Figure 20. Also the decrease in slump flow diameter and the increase of the time to reach this diameter as well as the time to reach the end of the horizontal compartment of the L-box in the L-Box test for increasing times at rest, as simple workability-test methods for the thixotropy, were comparable for both concretes.

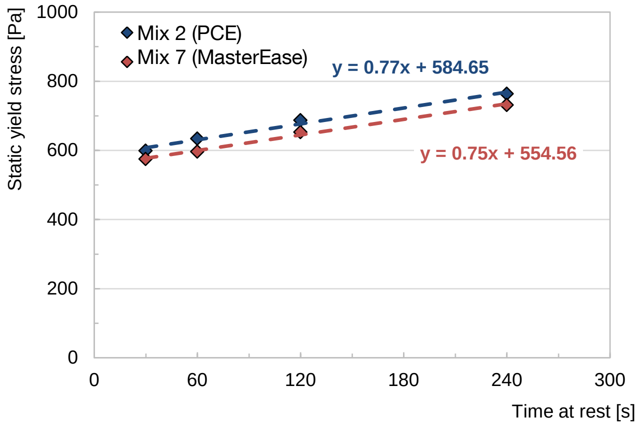

Figure 21: Increase in static yield stress of the reference mix (PCE) and the mix using an alternative SP (PAE) during time at rest as a measure of thixotropy

4.10 Mix 8 and Mix 9 – Variation in water-to-binder ratio

The purpose of the test series was to systematically vary the plastic viscosity of the concrete. Therefore, the water-to-binder ratio was varied. The water-to binder-ratio was adjusted by 0.45 (REF), by 0.50 and by 0.35. The compositions for the three concretes were made under the following two restrictions: 1) the paste (water and binder) volume was kept constant, and 2) the binder composition (ratio of cement-to-fly ash) was also kept constant.

The SP dosage of the mixes was adjusted to reach a comparable initial consistency (spread value, slump flow diameter) and dynamic yield stress. Starting from the SP dosage of the reference mix, the SP content had to be increased for the w/b=0.35 mix and, as expected, decreased for the w/b=0.50 mix. A significantly increased plastic viscosity for decreasing w/b ratios could be quantified in the rheometer test. Lower values for the calculated flow velocities in the slump flow test and the L-Box test confirmed this behavior. The measured values for the initial dynamic behavior of three concretes are shown in Table 2.

Table 42: Initial dynamic properties of the concrete with variation of w/b ratio

		w/b = 0.35	**w/b = 0.45 (REF)**	**w/b = 0.50**
Spread	[cm]	60.5	61.5	61.5
Dyn. yield value	[Pa]	98	108	103
Pl. Viscosity	[Pas]	111	21	10
Slump flow	[cm]	49.0	51.0	51.0
Slump flow time	[s]	10.0	5.5	3.8
L-Box flow time	[s]	9.7	2.3	1.6
L-Box filling height	[cm]	7.0	7.5	7.0

The dense particle packing of the highly viscous w/b=0.35 mix exhibited a pronounced increase in static yield stress during time at rest and thus the highest values for the thixotropy. This tendency was also confirmed by the workability tests (e.g. slump flow velocity at various times at rest).

The reference mix had favourable flow retention behavior. Until 2 hours at rest, all three mixes behaved in a similar manner, a comparable decrease of the slump flow diameter and thus a comparable increase of the dynamic yield stress could be observed. But, opposite to the w/b=0.35 and the w/b=0.50 mix, the reference mix (w/b=0.45) had a sufficient consistency (slump flow diameter ≈ 40 cm) even after 4 hours at rest, see Figure 21.

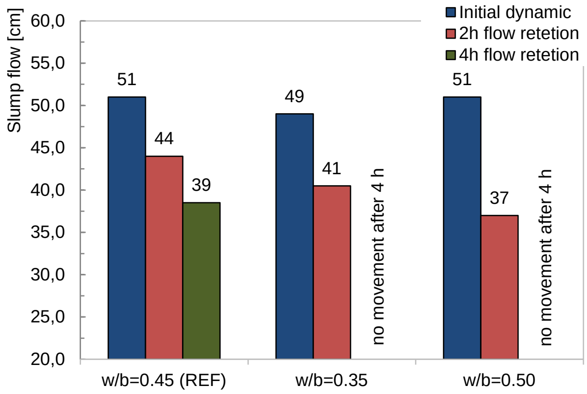

Figure 22: Development of the slump flow diameter during time at rest for w/b=0.35, w/b=0.45 (REF) and w/b=0.50

The reason for the workability loss of the w/b=0.50 mix may be the decreased dosage of the superplasticizer. This superplasticizer is especially used for long workability times and thus, its reduction may lead to an accelerated consistency loss of the concrete. Reasonable for the workability loss of the w/b=0.35 mix is the dense particle packing of the binder material, that in turn affects the reversible (thixotropic) and irreversible (workability loss) structural build-up of the concrete.

4.11 Mix 10 – High strength concrete by addition of silica fume (SF)

This test series was to account for the increasing requirements regarding the compressive strength of DFC. The effect of a replacement of 20 kg/m³ of the fly ash by silica fume on the fresh concrete properties has been investigated for this purpose. The superplasticizer dosage had to be increased for the mix containing silica fume in order to reach a comparable spread value to the other concretes. Except the partial replacement of the fly ash and the superplasticizer dosage, the material composition of Mix 10 was equal to the w/b=0.35 mix design of the previous test series. It is therefore named w/b=0.35+SF.

Both mixes showed comparable initial dynamic properties. Yield stress, plastic viscosity as well as the related workability test provided values in the same range for w/b=0.35 and w/b=0.35+SF.

In contrast, the partial replacement of fly ash by silica fume led to a decreased thixotropy, shown by an smaller increase of static yield stress during time at rest and by smaller changes in the slump flow velocity for the w/b=0.35+SF mix, see Figure 22.

Both mixes had almost similar flow retention behavior.

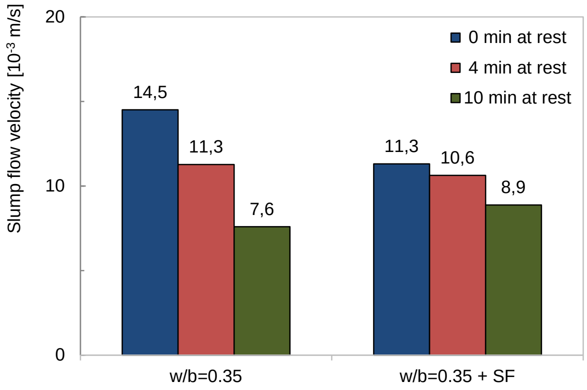

Figure 23: Development of the slump flow velocity during time at rest for w/b=0.35 and w/b=0.35+SF

4.12 Mix 11 – Variation in type of addition: Replacement of fly ash by limestone powder

The purpose of the test series was to determine the effect of a volumetric replacement of the fly ash of the reference concrete by limestone powder (“LSP”). The superplasticizer dosage had to be slightly increased for the LSP mix in order to reach a spread value, comparable to the reference mix. The other mixture composition is equal to the reference mix design.

The LSP mix had a lower plastic viscosity, compared to the reference mix, observed in lower flow times in the slump flow test and the L-Box test. In addition, the LSP mix led to an increase of the thixotropic structural built-up of the concrete during the first minutes at rest as well as an increased workability loss. Already after 2 hours at rest, the LSP mix did not spread and retained its shape after lifting the slump cone in the slump flow test. The measurement in the vane rheometer also showed a disproportionate increase in the static yield stress after 2 hours at rest.

4.13 Mix 12 – Reference concrete with consistency extender, 2nd product

The purpose of the test series was (in addition to test series no. 6) to determine the general effect of a consistency extender on the rheological behavior of the reference concrete. A consistency extender is an admixture which enhances the flow retention and thus prolongs the workability time of the concrete without the use of a classic retarding agent. A consistency extender “LZ.553” from Mapei was used for the test series. The other material composition of Mix 12 corresponds to the reference concrete (Mix 2) and the SP content was kept constant to reach a similar initial consistency. It was found that the concrete with the consistency extender led to an increased plastic viscosity and a pronounced thixotropy. Additionally, the consistency extender ha a positive effect on the flow retention of the concrete. Even after 4 hours at rest, all workability tests and rheometer measurements could be done with the concrete whereas the reference mix retained its shape in the workability tests, Figure 23. This advantageous behavior of the concrete containing the consistency extender is mainly due to the only slight increase of its plastic viscosity during time at rest.

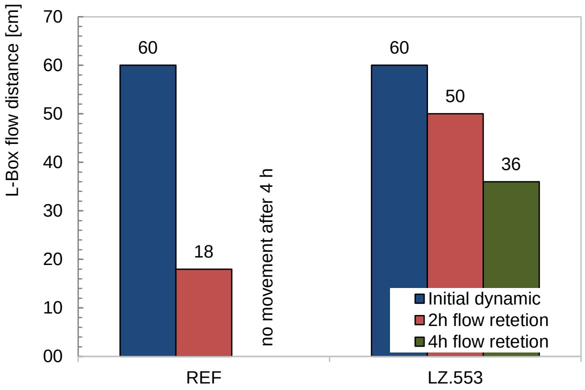

Figure 24: Development of the L-Box flow distance as a measure of the flow retention behavior of the reference mix (REF) and the mix containing a consistency extender (LZ.553)

4.14 Mix 13 – Variation in type of aggregate: rounded vs. crushed aggregates

This test series was to determine the effect of the type of aggregate used on the rheology and workability of DFC. The mix design of the reference concrete was used for this purpose and the naturally rounded aggregate that was used for the reference mix design was volumetrically replaced by crushed aggregates (crushed sand and crushed basaltic coarse aggregates). The grain size distribution of the aggregates was almost identical for the rounded and the crushes aggregates in order to exclude effects due to the grain size distribution, see Figure 24.

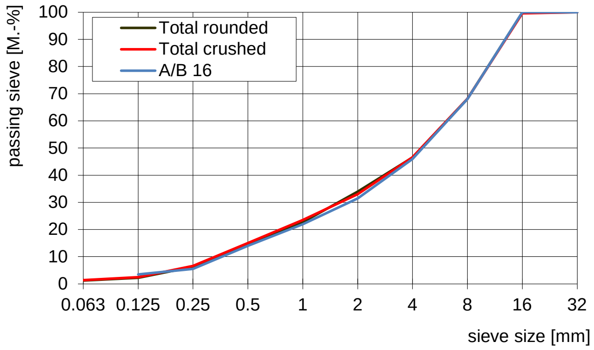

Figure 25: Grain size distribution of the rounded and the crushed aggregates

The concrete with the crushed aggregates (Basalt mix) had a slightly increased SP demand to reach the same spread as the reference mix. Additionally, the Basalt mix exhibited an increased plastic viscosity in the vane rheometer test, confirmed by lower flow velocities in the workability tests.

Thixotropy and flow retention (see Figure 25) of both concretes were comparable. This was as expected, since these properties are mainly affected by the paste composition of the concrete.

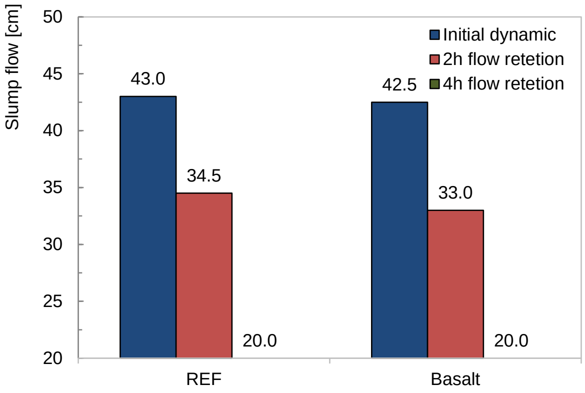

Figure 26: Flow retention of the reference concrete with rounded (REF) and with crushed (Basalt) aggregates

4.15 Outlook

The final step in the work package is the development of an advanced concrete mix design with regard to favourable initial dynamic, thixotropic as well as flow retention properties. This mix design was envisaged to be done, when all results of the documentation after excavation of the elements from WP01 were made available. As such advanced mix is not decisive for the conclusions and will only contribute to a better understanding how mixes could be improved for workability, this missing test is not considered critical for conclusions to be reviewed to provide recommended ranges for target values for rheology respectively workability as it is the aim for the 2nd Edition of the Guide to Tremie Concrete for Deep Foundations (2018).

5. WP 3: Rheological characterization of DFC by means of simple onsite tests

One aim of the R&D project was to identify simple workability tests, which are robust enough to be used on construction sites, to determine the rheological properties of DFC. This characterization has to cover three mainly time dependent parts: 1) the rheological behavior of the concrete in the fresh mixed (sheared) state after arrival on the construction site, 2) the change of the rheological properties due to thixotropic effects within a few minutes undisturbed at rest (not sheared) as a possible significant effect on the form filling properties and 3) the workability retention during concrete placement in the deep foundation element.

Furthermore, the rheological characterization by means of simple onsite tests has to cover both, a measure for the dynamic yield stress and the plastic viscosity of the concrete. Whereas the dynamic yield stress corresponds to a stress which has to be overcome to initiate concrete flow, the plastic viscosity can be understood as a term of cohesiveness and thus concrete flow velocity.

5.1 Initial Dynamic Properties

It can be concluded that the **dynamic yield stress** $\tau_{0,D}$ can accurate be calculated **by the slump flow diameter** *SF*, see Figure 27. The blue dots are single measurements of the slump flow diameters and the corresponding dynamic yield stresses of various DFC mixture compositions under lab conditions. These tests were performed within the frame of WP 2. The grey dots are the measured values for the investigated concretes during the fresh concrete testing on construction sites from WP 1. The black dashed line is a fitting function for all results (lab and field) based on a power law. The coefficient of determination for the power law fit is $R^2 = 0.94$ which identifies a good match.

The **plastic viscosity,** μ_{vane}, of the concretes can be derived **by** a calculation of the **slump flow velocity,** v_{SF},during the slump flow test, Figure 28. To calculate the slump flow velocity, the time t_{SF} [s] taken for the concrete to spread to the final slump flow diameter *SF* [mm] is measured. The travel distance (SF - 200)/2 [mm] divided by the time taken t_{SF} [s] is the slump flow velocity v_{SF} [mm/s].

Again, the blue dots are the lab results of WP 2, the grey dots are the field results of WP 1 and the black dashed line is a power law function as the best fit of all results (lab and field).

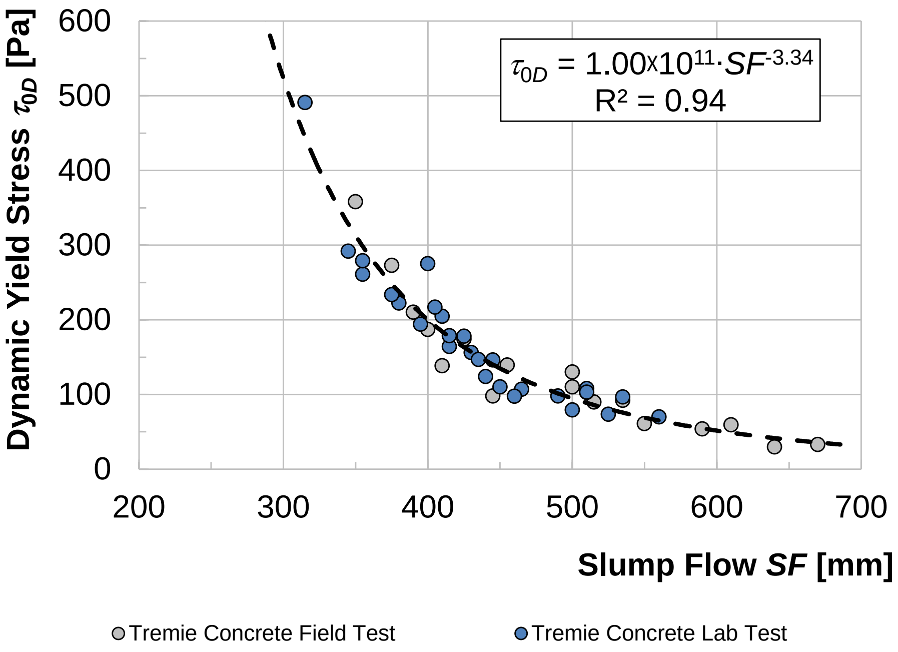

Figure 27: Dynamic yield stress as a measure of slump flow diameter

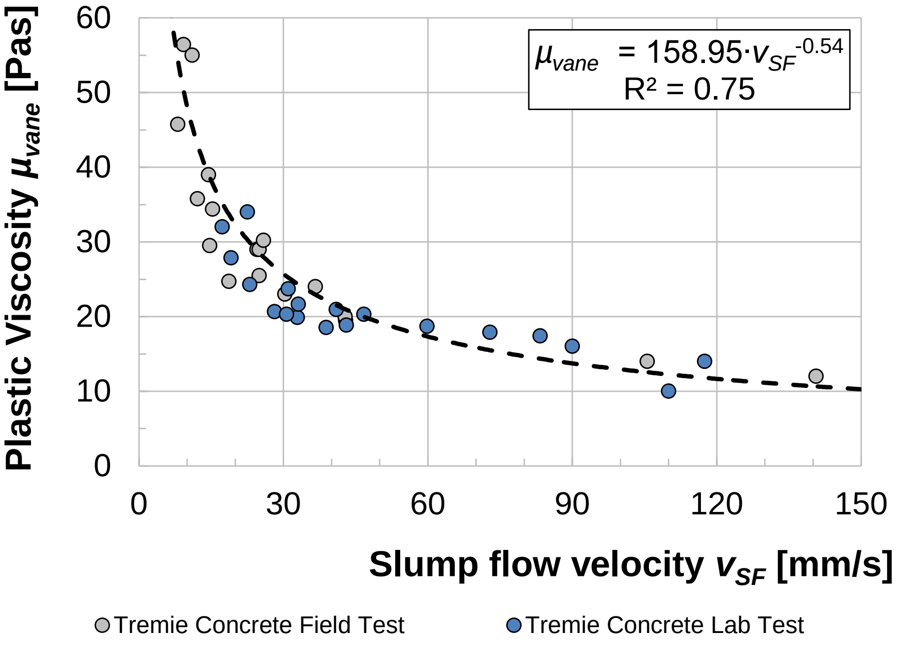

Figure 28: Plastic viscosity as a measure of slump flow velocity

Reviewing the US results and using the same set-up for evaluating the rheological parameters from the ICAR rheometer, it can be seen that also the US results follow the same trend as found for the European test results, and in particular cover the same range of corresponding slump flow and slump flow velocity values, see Figure 29 and Figure 30.

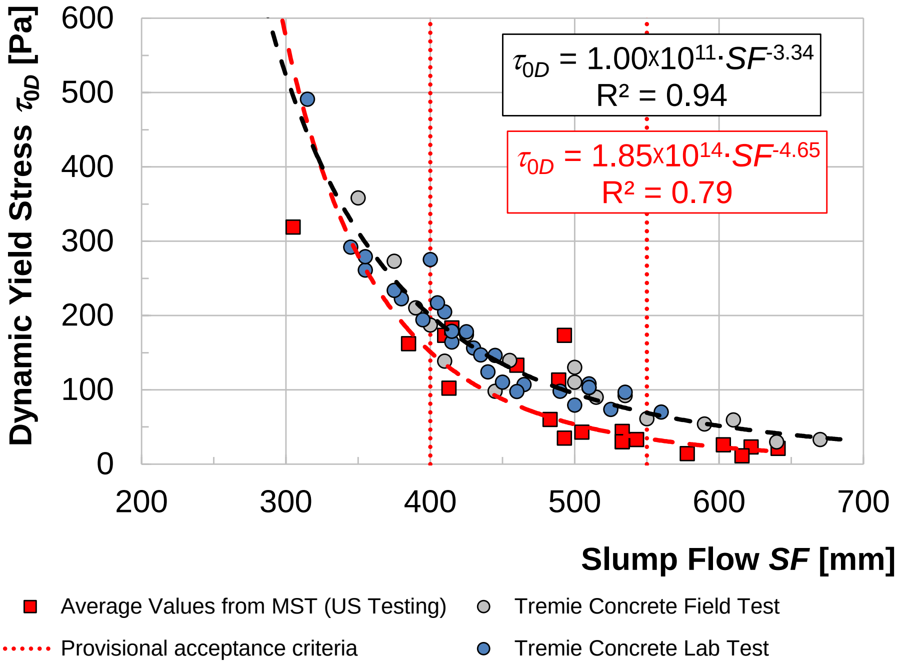

Figure 29: Dynamic yield stress as a measure of slump flow diameter (EU-results: grey dots, blue dots, black dashed line as power law fit; US-results: red squares, red dashed line as power law fit)

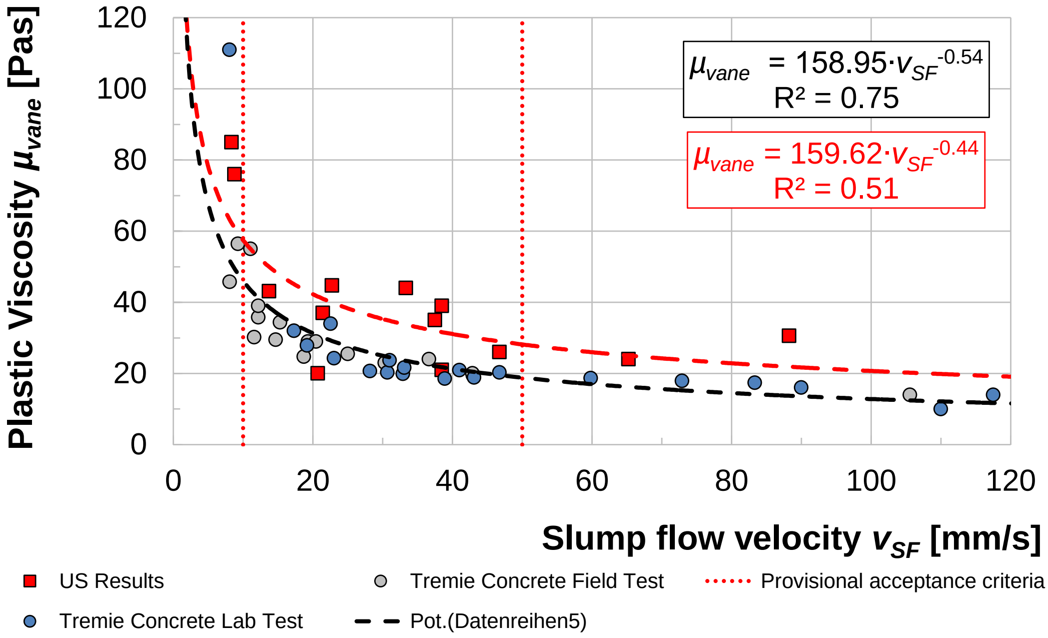

Figure 30: Plastic viscosity as a measure of slump flow velocity (EU-results: grey dots, blue dots, black dashed line; US-results: red squares, red dashed line as power law fit)

The remaining offset of test data evaluated by Missouri S&T compared to the test data evaluated by TU Munich is obviously linked to the determined plastic viscosity gained from the two rheometers used in Missouri and Munich. This offset is assumed to be caused by the device, by their settings or a different handling, but not critical in its degree. In addition the US data seem to scatter more. The trend is still definite.

5.2 Thixotropy

The thixotropic increase of the static yield stress in the vane rheometer test can also be observed by decreasing values of the slump flow or the L-Box flow distance as well as increasing values for the time to reach these flow distances. Further experiments have to be done to enable the quantification of a precise relationship between the rheometer values and the values given by the workability tests.

The increase of the dynamic yield stress for longer times at rest (in terms of the quantification of the flow retention properties) can also be predicted by the decreasing slump flow diameter.

In conclusion, the simple slump flow test may be suitable to discover a high tendency of the specific concrete mix to stiffen due to thixotropy. A considerable and still practicable resting time in the truncated cone for the slump flow test to allow a certain structuration (thixotropic built-up) should be a minimum of 10, or better 15 minutes. If after this resting time the resulting slump flow is, compared to the initial slump flow decreased by 50 mm or more, it might be worth checking the concrete's tendency for thixotropy and its effects on concrete placement in more detail. In any event, due to the accuracy of the slump flow test (of about 30 mm) a structuration found in one pair of tests (initial and 15 mins) should be repeated to validate the finding.

For a more accurate determination of any thixotropic tendency, the manual vane shear tester could be used. By measuring the static yield stress over time, a relevant value to indicate thixotropic behavior can be derived. From studies done within this EFFC R&D program there are not sufficient results. According to Roussel and Cussigh, 2008, a 100% increase in 15 minutes may be assessed as excessive thixotropy. Smaller structuration rates might already be relevant but this assessment is beyond the scope of this R&D program.

5.3 Workability retention

As for the determination of thixotropy, the workability retention can be reliably tested (and proven) by the slump flow test. The slump flow has therefore to be tested and recorded at discrete intervals over the designated time.

However, it has been found that the concrete which has been kept in the truncated cone of the slump flow test for 2 hours did not flow at all, i.e. showed insufficient workability, although it was retarded to a much later age.

In the test series on construction sites, this happened as can be seen by comparing the flow retention behaviour of the concretes of producer II, III, IV and V where the concrete retained its shape after lifting the cone after 2 hours at rest.

Obviously, allowing the concrete to rest before performing the slump flow test can allow other effects to mask workability loss. As a consequence, when determining the workability retention the concrete should be agitated (remixed) before the actual test so that no thixotropic structuration can take place for determining the available flowability over time. For the practical relevance this implies that concrete is also sufficiently sheared in the deep foundation element to retain its required workability until it is finally placed.

Note: Any stiffening of the concrete mix by thixotropy should be covered by testing the concrete's shear stress (or slump flow) after a certain time at rest, see 5.2.

6. WP 4: Development of a practice-oriented suitability test concept and on-site workability test set for fresh deep foundation concrete based on rheology

Based on the findings from work packages WP1 to WP3 on rheology and workability of deep foundation concrete, the following set of tests could be used for suitability testing in the concrete design process (usually in the laboratory) and for acceptance testing on site.

For discrete properties there might be more than only one test which can replicate this. Regarding the yield stress, for example, beside the vane rheometer, the slump test, the flow table test and the slump flow test were used. Even results from the manual vane shear tester or from the L-Box can be correlated with the yield stress. Where several tests might be applicable in principal to describe a certain property, advantages and disadvantages are briefly discussed, by intention without discriminating against any of them.

Note: The tests used in the R&D program were already pre-selected from a number of many more tests available on the market or on a scientific studies level. Therefore, it should be noted, that other tests (outside this program) may be able to deliver significant values for key rheological parameters

With respect to the stability of fresh tremie concrete, tests will also be discussed which can be used to detect the main issues as defined for tremie concrete, from the joint EFFC/DFI concrete task group. These are segregation, bleeding and filtration.

Workability:

As already pointed out, the rheology of DFC is a physical indicator for workability and therefore the yield stress and the viscosity should be able to be – indirectly – tested.

Workability tests as a measure of Yield Stress

Slump flow test:

This is a good and simple test method. It is applicable in the laboratory and on construction sites. It had a very good correlation to the yield stresses measured by the vane rheometer. It was sufficiently reliable over the wide range of yield stresses found in the concrete mixes tested.

Slump test:

This is also a good and simple test method. It is applicable in the laboratory and on site. It is proven to have a good correlation to the yield stress of concrete mixes but only up to a certain value. Flowable mixes with slump flow values of 400 to 550 mm, as used in the field (for real projects), had slump values of 220 to 270 mm, i.e. above 210 mm. These slump values comprise two issues:

1) The EN 206:2013 + A1:2016 state in Appendix L that the testing range should be limited to a maximum of 210 mm which is below most of the values found in the field.
2) Taking into account a tolerance for the testing accuracy of 30 mm (see also EN 206) it seems insufficiently sensitive to distinguish mixes within the range of flowable mixes.

Where slump is used for suitability, or later for acceptance testing, it should be considered to establish a correlation between the yield stress (or the slump flow as a substitute), and the slump for the specific concrete mix being established.

Note: The slump values of 220 to 270 mm for the mixes tested in the field program were assessed to be relatively high in comparison to correlations found in the literature, but consistent throughout the test program.

Flow table test:

This is a good and simple test method. It is applicable in the laboratory and on site. It is proven to have a good correlation to the slump flow in the mixes used for the R&D studies. It was also sufficiently reliable over the wide range of yield stresses found in the concrete mixes tested. But, in comparison to the slump flow with a 150 mm range of values (400 – 550 mm), the associated range of values was only 80 mm (560 – 640 mm) for the flow table test, which reveals a lower sensitivity. Additionally taking into account a tolerance for the testing accuracy of 40 mm (see EN 206:2013 + A1:2016 state in Appendix L), it is also questionable if the remaining reliability is enough to distinguish mixes within the range of flowable concrete mixes.

Further investigation is also required on the relevance of the dynamic impacts which seem not to reflect the actual situation during a pour in deep foundations where no mechanical vibrations are applied to the concrete to overcome the static yield stress.

Modified cone outflow test:

This test has a direct correlation with viscosity. It also provides, in comparison to the simpler inverted cone outflow test using only the Abraham’s cone, a higher sensitivity and accuracy. This is due to the increased volume and due to the flap by which the concrete is forced to freefall immediately and cannot be influenced in its free flow by an individual manual cone lifting process.

Slump Flow Velocity test:

This is a good and simple test method. It is applicable in the laboratory and on site. Taking the time during the slump flow test allows, with little additional effort, an easy determination of the viscosity. However, due to the individual observation and decision when a concrete flow is stopped, the accuracy of this test is limited. Therefore it should be considered to only apply this test for classification whether a concrete is highly or rather low viscos but not as a direct measure to precisely quantify concretes viscosity.

Stability:

Manual Vane Shear Test:

This is a direct test method to quantify the static yield stress. With respect to the effective measuring range the standard hand vane shear tester in the field of ground engineering must be enlarged to get the shear stresses into the measurable range.

VSI:

Good and simple test method. It is applicable in the laboratory and on site. The Visual Stability Index can be derived, practically without any extra effort, from the slump flow test.

Segregation:

Any test can be used which allows the measurment of segregated particles. The ASTM or the Wash-out test are based on sieving the coarse aggregate from the upper and lower portion of a cylinder, but the test has to cease before initial set in order to allow the washing-out of the aggregates. Cutting a cylinder after hardening allows the visual evaluation of segregation over the full height. This automatically implies that the full segregation potential is covered by this test, but it takes longer to get a result and the determination of coarse aggregate fractions over height needs specific training and tools if high precision is requested.

The sieve segregation test has been shown to have a good correlation with the Wash-out test, both can therefore be used to evaluate concrete segregation.

Bleeding:

Even if bleeding was not the subject of the R&D project it is obvious that it has to be taken into account in order to guarantee high quality of deep foundation elements. It is recommended to carry out bleeding tests in accordance with EN 480-4 and ASTM C232. As the small scale test is not undoubtedly to simulate accurately the full scale bleeding in a deep foundation, in particular in its rate over time it is therefore understood that a “good bleed result” may still not proof a high stability of fresh concrete, but that a “bad result” indicates insufficient stability, i.e. this test can be used for negative selection.

Filtration:

The Bauer filtration test was found to be suitable for all concretes tested within this R&D project. It is therefore recommended to perform that test or alternatively the Austrian filter press test in order to evaluate filtration behaviour of Tremie concretes under pressure.

7. WP 5: Requirements related to the mix-design of concrete in deep foundations

It was the aim of work package WP5 to assess all available data from work packages WP1 to WP4 and to develop recommendations for appropriate acceptance criteria for DFC. The casting of a deep foundation element seems simple on the surface but there are many factors which affect the flow patterns including, but not limited to, the density of the support fluid, the clear spacing of the rebars, the number of rebar layers, the tremie embedment and the horizontal flow distance inside the excavation.

As a consequence, it is not possible to set absolute values. Ranges are recommended for specific properties from which individual target values should be chosen (as shown in Table 43). The individual target value should be set by the specifier who has sufficient information and knowledge to make a reasonable engineering assessment.

Although not obvious from the beginning, the major fresh concrete property with regards to the flowability and filling ability (including also the passing ability*), is the yield stress.

* here seen only from the perspective of a bulk fluid, i.e. blocking due to coarse aggregate accumulation is not considered.

Acceptance criteria for deep foundation (tremie) concrete might be considered within the ranges indicated in Figure 31 and Figure 32:

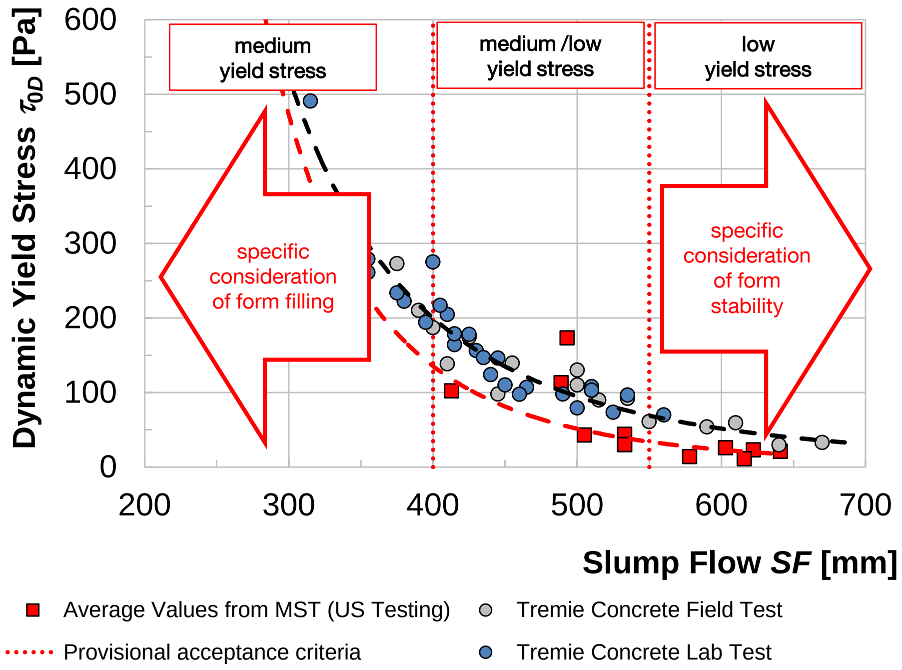

Figure 31: Dynamic yield stress as a measure of slump flow diameter

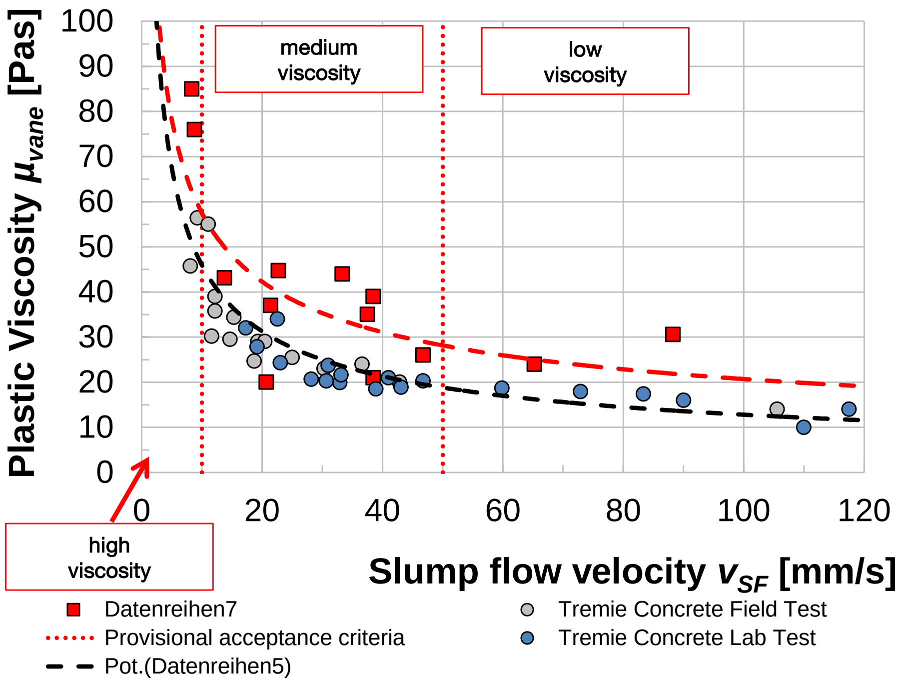

Figure 32: Plastic viscosity as a measure of slump flow velocity

It should be noted that the relation between slump flow and spread (or slump) from other tests are able to represent the yield stress of fresh concrete, see **Figure 33**.

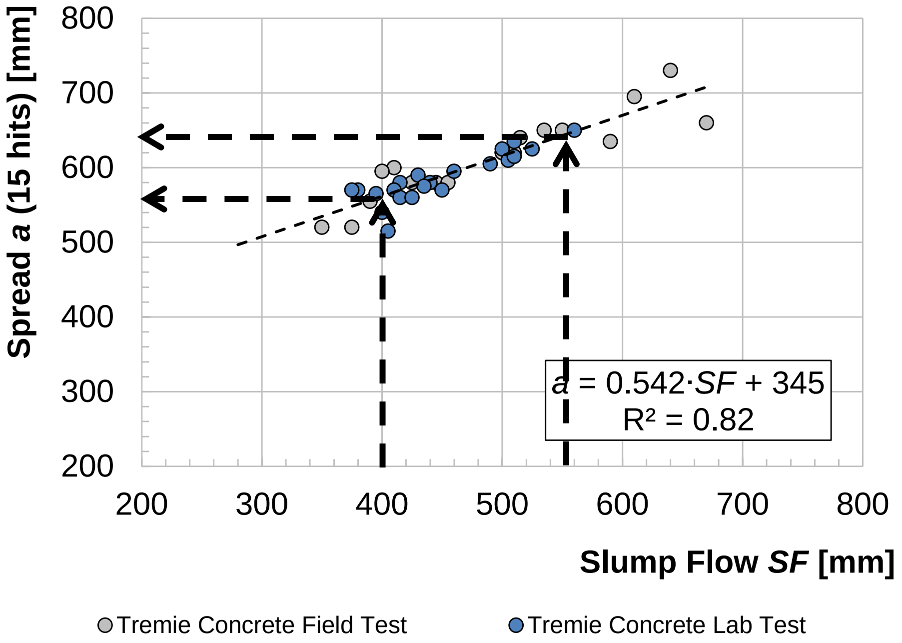

Figure 33: Spread (flow table test) in relation to slump flow (slump flow test)

Table 43: Recommended ranges for acceptance criteria for Tremie concrete

Test	Recommended values
Slump Flow Slump Flow Velocity VSI	400 – 550 mm 10 – 50 mm/s 0
Flow Table	560 – 640 mm
Modified Cone Outflow	3 – 6 s
Workability Retention	≥ 400mm
Bauer Filtration	≤ 22 ml

8. Summary

This R & D Report comprises results from 5 Work Packages dealing with fresh properties of Tremie Concrete for Deep Foundations.

Based on the results and assessments of investigations in Europe and the US, in the laboratory and in the field, and also considering findings from Numerical Modelling studies carried out in parallel, reliable information has been provided to specify the requirements for fresh tremie concrete.

These requirements are given as recommended ranges from which a suitably qualified person can select an appropriate target value for the conditions in which the specific element has to be poured.

For all target values it is further obligatory to specify a tolerance for acceptance which should reflect both the sensitivity of the individual test method and the accuracy to which the property is essential.

The slump flow test was found to be the most suitable test method since it combines three major results:

1) Calculation of the slump flow diameter as a measure of yield stress
2) Calculation of slump flow velocity as an indication of the concrete's viscosity range
3) VSI as a visual fast check of concrete homogeneity

Furthermore, the concrete flow retention behavior can be evaluated by repeating the slump flow test at several points in time.

It was found out the concretes with a high slump flow (> 550 mm) may be prone to stability issues whereas low slump flow concretes (< 400 mm) may lead to insufficient form filling inside the deep foundation element.

9. Outlook

It is believed that future developments in numerical modelling can help to assist the specifier in determining relevant target values for a specific condition to pour concrete in a deep foundation.

Having a new Guide to Tremie Concrete with new recommendations for fresh concrete design applied in practice, after a certain period of experience it is hoped that these new recommendations will help in reducing imperfections due to insufficient concrete behavior (if those could be traced back at all), or in total.

10. References

(EFFC/DFI, 2016) EFFC/DFI, 2016: *Best Practice Guide to Tremie Concrete for Deep Foundations*. European Federation of Foundation Contractors, UK, and Deep Foundation Institute, USA

(Kraenkel et al., 2016) Kraenkel, T., et al., 2016: *Rheology Testing of Deep Foundation Concrete*. 25th Conference on Rheology of Building Materials, University of Technology Regensburg, Germany, ISBN: 978-3-7345-1313-8

(Feys et al., 2018) Feys, D., et al., 2018: *Testing Concrete for Deep Foundations – Progress report, May 2018.* Missouri University of Science and Technology