

TESTING CONCRETE FOR DEEP FOUNDATIONS

PROGRESS REPORT (MAY, 2018)

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Table of Contents

1	Introduction	3
2	Mix designs of lab mixtures	4
3	Laboratory tests	6
3.1	Work Plan	6
3.2	Test methods	6
3.2.1	Mixing procedure	6
3.2.2	Slump flow, T_{50} , T_{Final}	7
3.2.3	Dynamic rheological properties.....	7
3.2.4	Static Stability	7
3.2.5	Bleeding of concrete.....	8
3.2.6	Bauer filter press.....	8
3.2.7	L-box	8
3.2.8	Isothermal calorimetry.....	8
3.2.9	Initial and final set	8
3.2.10	Compressive strength.....	8
3.3	Test results immediately after mixing, setting times, and strength	8
3.4	Time evolution of workability and rheological parameters	11
3.5	Thixotropy	17
4	Comparing US Lab and Field Tests.....	25
5	Summary	35
6	Acknowledgments	36

1 Introduction

This report is a summary of the test results conducted for the Deep Foundations Institute (DFI), which were conducted to evaluate the fresh and key hardened properties of concrete mixtures used in the field. 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, seven mixtures need to be evaluated. At the moment of the writing of this progress report, six mixtures had been evaluated. The mixtures from the different producers are named A to G, 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. In some cases, the other admixture quantities are also modified. 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.

2 Mix designs of lab mixtures

Table 1 to Table 6 show the mix design for producer A to F, respectively. The field mix designs were obtained from the reports on the performance of the fresh mixtures sent to the research team. A trial batch was made for each mix design, keeping the constituent materials constant, but modifying the chemical admixture quantities, mainly the (high-range) water-reducing agent(s) ((HR)WRA), to ensure an initial slump flow after mixing close to the reported value in the field. Changes in mixing energy, testing and potentially the moisture content of the aggregates are likely to modify the workability of concrete. Hence, it was opted for a change in WRA content, rather than just reproducing the mixture, risking either segregation or insufficient flowing ability.

The following should be taken into account for the remainder of the report. For mix design B, the field mix design did not yield the corresponding slump flow (as the research team took the average reported slump flow value, instead of the value of one report), even when three times the amount of HRWRA was added. The research team decided to increase the paste volume by 5% as the mixture appeared to be lacking paste and contained too much sand. For mix design C, the required HRWRA dosage in the lab was about half of what is required in the field. When preparing the batch for the testing series, the same amount of HRWRA was added, yielding a slump flow that was slightly larger than the reported field value. For mix design D, the research team discovered some issues with the delivered cement that had large lumps. This led to heavily segregating concrete before addition of the HRWRA. It was decided to replace the delivered cement with a local Type I/II cement. Furthermore, it was discovered that producer D used recycled water, which is impossible to replicate in the laboratory. It should also be noted that mix design F contained a substantially higher slag content (50%) compared to all other mixtures (0-25%).

Table 1. Field and lab mix designs for producer A.

	FIELD (KG/M³)	FIELD (LBS/YD³)	LAB (KG/M³)	LAB (LBS/YD³)
3/4" ROCK	527	889	527	889
3/8" ROCK	311	524	311	524
SAND	847	1428	847	1428
CEMENT	311	525	311	525
FLY ASH	89	150	89	150
WATER	170	287	170	287
AEA	0.05	0.09	0.05	0.09
WRA	3.13	5.28	2.35	3.96
HRWRA	2.01	3.39	4.02	6.78
RETARDER	1.31	2.20	1.31	2.20

Table 2. Field and lab mix designs for producer B.

	FIELD (KG/M³)	FIELD (LBS/YD³)	LAB (KG/M³)	LAB (LBS/YD³)
3/8" ROCK	846	1425	830	1399
SAND	828	1396	813	1370
CEMENT	214	360	220	371
FLY ASH	107	180	110	185
SLAG	107	180	110	185
WATER	206	347	211	356
STABILIZER	2.24	3.78	2.31	3.90
HRWRA	3.87	6.52	3.99	6.72
RETARDER	2.79	4.69	2.87	4.84
VMA	2.24	3.78	2.31	3.90

Table 3. Field and lab mix designs for producer C.

	FIELD (KG/M³)	FIELD (LBS/YD³)	LAB (KG/M³)	LAB (LBS/YD³)
3/8" ROCK	611	1030	611	1030
SAND	1078	1816	1078	1816
CEMENT	234	395	234	395
FLY ASH	119	200	119	200
WATER	174	293	174	293
AEA	0.06	0.10	0.06	0.10
HRWRA	1.71	2.89	0.86	1.44
RETARDER	1.38	2.32	1.38	2.32

Table 4. Field and lab mix designs for producer D.

	FIELD (KG/M³)	FIELD (LBS/YD³)	LAB (KG/M³)	LAB (LBS/YD³)
3/4" ROCK	772	1302	772	1302
3/8" ROCK	258	434	258	434
SAND	608	1024	608	1024
CEMENT	357	602	357	602
FLY ASH	89	150	89	150
WATER	173	292	173	292
AEA	0.08	0.13	0.08	0.13
HRWRA	1.02	1.71	0.36	0.6
RETARDER	1.16	1.96	1.16	1.96

Table 5. Field and lab mix designs for producer E.

	FIELD (KG/M³)	FIELD (LBS/YD³)	LAB (KG/M³)	LAB (LBS/YD³)
3/8" ROCK	951	1602	951	1602
SAND	720	1213	720	1213
CEMENT	223	375	223	375
FLY ASH	112	188	112	188
SLAG	112	188	112	188
WATER	176	296	176	296
HRWRA	1.43	2.41	3.67	6.19
RETARDER	2.90	1.96	6.38	10.76
STABILIZER	1.16	4.89	1.16	1.96
VMA	2.90	4.89	1.47	2.48

Table 6. Field and lab mix designs for producer F.

	FIELD (KG/M³)	FIELD (LBS/YD³)	LAB (KG/M³)	LAB (LBS/YD³)
1/2" ROCK	890	1500	890	1500
SAND	901	1518	901	1518
CEMENT	128	216	128	216
FLY ASH	85	144	85	144
SLAG	214	360	214	360
WATER	178	300	178	300
HRWRA	3.49	5.88	5.05	8.51
WRA	1.60	2.69	1.66	2.80
RETARDER	2.15	3.63	2.24	3.78
STABILIZER	1.39	2.34	2.24	3.78
VMA	2.15	3.63	2.24	3.78

3 Laboratory tests

In this section, the laboratory test results are summarized for all mixtures, and some comparisons between different parameters are established.

3.1 Work Plan

After the determination of the admixture demand to establish the initial slump flow reported during the field tests for each mix design, the concrete mixtures were batched twice to perform the following tests:

- Tests immediately after mixing:
 - Slump flow (cone in normal position)
 - T_{50} (mixtures A, B, C)
 - T_{final} (mixtures D, E, F)
 - Dynamic rheological properties with the ICAR rheometer
 - Column segregation resistance
 - Sieve Stability test (mixture D, E, F)
 - Bleeding and rate of bleeding
 - Bauer Filter Press
 - L-box and L-box flow time (mixtures A, B, C)
- Tests repeated at 2, 4 and 6 hours to evaluate workability loss:
 - Slump flow (cone in normal position)
 - T_{50} (mixtures A, B, C)
 - T_{final} (mixture D, E, F)
 - Dynamic rheological properties with the ICAR rheometer
- Evaluation of thixotropic properties:
 - Static yield stress (ICAR) at 0, 30, 60, 120, 240, and 600 s
 - Static yield stress (Portable Vane), at 0, 15, 30, and 60 min
 - Difference between immediate and delayed (4 min) slump flow (mixtures A, B, C)
 - Difference between immediate and delayed (4 min) L-box (mixtures A, B, C)
 - Compressive strength at 28 days
 - Initial and final setting time on sieved mortar
- Evaluation of isothermal calorimeter profiles on reproduced pastes (mixtures A, B, C) and the sieved mortar (mixture D). However, there seems to be an issue with the calorimeter and the data are not fully reliable.

3.2 Test methods

3.2.1 Mixing procedure

For all mixtures, the following mixing procedure was employed:

- All aggregates, half of the mixing water and the air-entraining agent were added and homogenized for 30 s.
- The cement and cementitious materials, and the remaining part of the mixing water was added and mixed for 1 min.
- The HRWRA was added and mixing continued for 1 min.
- All other admixtures were incorporated and the mixtures was mixed for another minute

- Mixing was stopped for three minutes and the walls of the mixer were scraped to ensure the mixture was homogeneous
- Mixing was resumed for two minutes.

Prior to all testing, including testing at extended time, the mixture was remixed for approximately 30 s to ensure homogeneity and thixotropic breakdown. In between tests, the mixture was slowly agitated in the mixer, while the mixer opening was covered to minimize water evaporation. Non-segregated concrete from slump flow, L-box and rheology testing was put back in the mixer in between tests. Logically, concrete from segregation and bleeding tests was not reused.

3.2.2 Slump flow, T_{50} , T_{final}

The slump flow measurement was executed according to ASTM C1611-14, by placing the Abrahm's cone straight up (not inverted). No consolidation was applied to the concrete sample. The slump flow was taken as the average of two orthogonal diameters. Although the inverted cone test is more user-friendly as only one operator is needed to perform the test, the straight up cone slump flow result can be easily related to the yield stress. In case of an inverted cone, the concrete must deform and drop, and relationships between slump flow and yield stress, and between T_{50} or T_{final} and viscosity are more difficult to achieve. The T_{50} corresponds to the time needed to reach a 500 mm (20 in.) slump flow. The T_{final} is the time needed for the concrete to come to a complete stop.

3.2.3 Dynamic rheological properties

The ICAR rheometer was used to assess the rheological properties of the concrete. This rheometer consists of a four-blade vane with a radius of 63.5 mm and a height of 127 mm, rotating in a bucket with a 143 mm radius, leaving a gap space of 80 mm between the vane and the bucket. The procedure employed consisted of a 20 s pre-shear period, keeping the rotational velocity constant at 0.5 rps. The rotational velocity was then decreased in 10 steps from 0.5 to 0.03 rps, the duration of each step being 5 s.

The analysis was performed on the raw data set. For each step, the first second was eliminated to avoid the influence of transitional behavior. The remaining torque data was checked for equilibrium: torque needs to be approximately constant with time. It should be noted that large fluctuations in the torque values are present and render this evaluated process more difficult. If no equilibrium was achieved, the data point was eliminated. At each rotational velocity step, the torque value was corrected based on a measurement in empty configuration, as the research team has noted that the empty measurement delivers slightly negative torque values.

The Reiner-Riwlin equation was applied on the data set. These equations transform the relationship between torque and rotational velocity into rheological parameters. Applying the following relationship on the torque (T) and rotational velocity (N): $T = G + H N$, G is the intercept with the T axis and H is the slope of the line. The Reiner-Riwlin equation transforms G into the yield stress and H into plastic viscosity. However, the resulting values of the rheological properties are only valid if the entire flow domain between vane and bucket is sheared, which is mostly not the case with the ICAR rheometer. An iterative procedure, developed by the research group, is applied to take the effect of this reduced shearing zone into account, resulting in more correct rheological properties. It should however be noted that measuring the rheological properties of low to medium slump concrete in the ICAR rheometer (or in any concrete rheometer) is a challenge, as the thickness of the sheared zone may become smaller than the maximum aggregate size. In that case, the measurement is invalid, which has been the case for the concrete from producer D.

3.2.4 Static Stability

The static stability of the concrete was determined by means of the column segregation test, described in ASTM C1610 – 17. The total segregation is calculated by taking the difference in mass of coarse aggregates in the bottom and the top section, divided by their average.

A second assessment of static stability was performed by means of the sieve stability test, described in the European Guidelines for SCC. This test consists of pouring 5.0 ± 0.2 kg of concrete on a number 4 sieve, from approximately 0.5 m high. The mass of mortar percolating through the sieve on a pan is determined after 2 min of rest. The sieve stability index is calculated as the percolated mass of mortar divided by the initial mass of concrete. It should be noted that the European Guidelines for SCC prescribe a 15 min waiting period between sampling the concrete and executing the test, presumably to increase the level of segregation. However, this period can also stiffen the concrete due to thixotropic build-up and result in a lower segregation value. The 15 min period was not included in the performed tests. As such, the concrete was poured immediately after sampling on the sieve.

3.2.5 *Bleeding of concrete*

The bleeding of concrete was evaluated based on ASTM C232. Two parameters were determined: the total bleeding, and the rate of bleeding in 30 min intervals.

3.2.6 *Bauer filter press*

The Bauer press test was performed for a total duration of 30 min, under a pressure of 100 psi. The total amount of water expelled from the concrete sample was reported.

3.2.7 *L-box*

The L-box is a test recommended in the European Guidelines for SCC to evaluate the passing ability of concrete. An outcome of the test is H_2/H_1 : the height of the concrete at the end of the box divided by the height of the concrete at the beginning of the box. The time needed to reach the end of the box was also recorded.

3.2.8 *Isothermal calorimetry*

The heat emitted by reacting cement paste is measured by means of isothermal calorimetry. The calorimeter curve is obtained by expressing the amount of heat (J) per hour, per gram of cement. Of particular interest for this project is the duration of the induction period. Theoretically, the inflection point after the end of the induction period should coincide with either initial or final set of the mixture.

3.2.9 *Initial and final set*

The setting times are evaluated according to ASTM C-403. A fresh concrete sample is reduced to mortar by wet sieving. The mortar is placed in a container, covered with a wet towel and stored under laboratory ambient conditions. Then, the resistance of the mortar to penetration by standard needles is measured at varying time intervals. The time spacing between penetration tests depends on the rate of setting of the mortar sample. Once that the penetration resistance exceeds 27.6 MPa, the times of initial and final setting are determined at the interception of 3.5 and 27.6 MPa respectively with a best fit line computed from a penetration resistance vs time plot.

3.2.10 *Compressive strength*

The compressive strength has been determined on three cylinders measuring 100 mm (4 in) in diameter and 200 mm (8 in) in height, according to ASTM C39. The strength was determined after 28 days of moist-curing.

3.3 **Test results immediately after mixing, setting times, and strength**

Table 7 shows the results of all tests conducted immediately after mixing, as well as the values for the initial and final setting times and the compressive strength at 28 days. A detailed analysis on the relationships between workability and rheology will be made in the next section. Figure 1 shows the static segregation (by means of the column segregation test), total bleeding and filter press forced bleeding for mixtures A to F. Figure 2 shows the bleeding rate of the mixtures evaluated in the laboratory. The graph shows the

accumulated bleeding water as a function of time. The slope is calculated by fitting a straight line through the data points, starting at the last data point showing 0 bleeding.

Figure 3 shows the isothermal calorimeter profiles of mixtures A to D. All mixtures were measured in pairs (see legend). Comparing the profiles in Figure 3 to the setting times reported in Table 7, a discrepancy can be noted between both measurements. Although no clear reason has been identified to explain this discrepancy, a potential cause could be in the different interactions of the admixtures with the materials in the reproduced cement paste and in the produced concrete mixtures.

Table 7. Results from initial test methods, setting time and strength. Values in italic are doubted by the research team (Rheological properties mix design D)

TEST METHOD	UNIT	PROD. A	PROD. B	PROD. C	PROD. D	PROD. E	PROD. F
SLUMP FLOW	(mm)	622	489	616	493	410	460
SLUMP FLOW	(in)	24.5	19.25	24.25	19.4	16.1	18.1
T50	(s)	8	3.9	-	-	-	-
TFINAL	(s)	-	-	-	6.7	2.73	6.28
YIELD STRESS	(Pa)	23	113	11	173	173	133
PLASTIC VISCOSITY	(Pa s)	85	21	54	8	21.4	19.2
COLUMN SEGREGATION	(%)	7.4	4.1	13.5	8.7	6.8	-
SIEVE STABILITY	(%)	-	-	-	1.3	0.0	0.1
BLEEDING	(ml)	32	50.5	9.5	35.2	57.1	75.4
BLEEDING RATE	(ml/hr)	3.65	9.14	4.58	6.49	11.64	17.04
BAUER FILTER PRESS	(ml)	30.1	49.4	25.3	43.0	41.1	40.7
L-BOX H2/H1	(%)	26	39	57	-	-	-
L-BOX FLOW TIME	(s)	22	3	3.6	-	-	-
INITIAL SET	(hr)	28	25.5	42.5	13.5	66.5	67.25
FINAL SET	(hr)	30	28	46.5	17	78	118
COMPRESSIVE STRENGTH	(MPa/psi)	47 / 6800	40 / 5890	47 / 6800	38 / 5530	43 / 6060	61 / 8770

Table 7 also shows the results for the sieve stability test, indicating no segregation for mixtures D, E and F. Although the sieve stability test has given very satisfactory results to the research team in characterizing the stability of SCC, no conclusion can be made whether this test is applicable towards concrete for deep foundations. The sieve stability test delivers very low values for the three evaluated mixtures (< 1.5%). Further testing may be needed to evaluate whether the sieve stability test can distinguish between segregating and stable concrete for deep foundations.

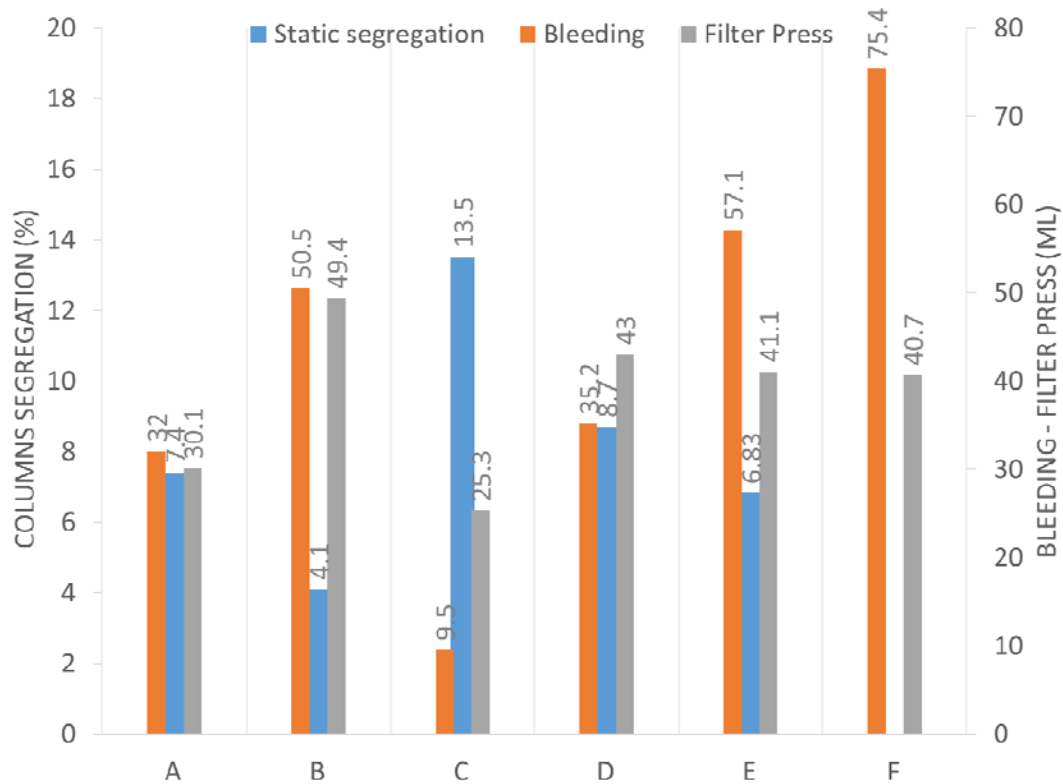


Figure 1. Static segregation by means of column segregation (blue), total bleeding water (orange) and total filter press water (grey) for mix design A to F.

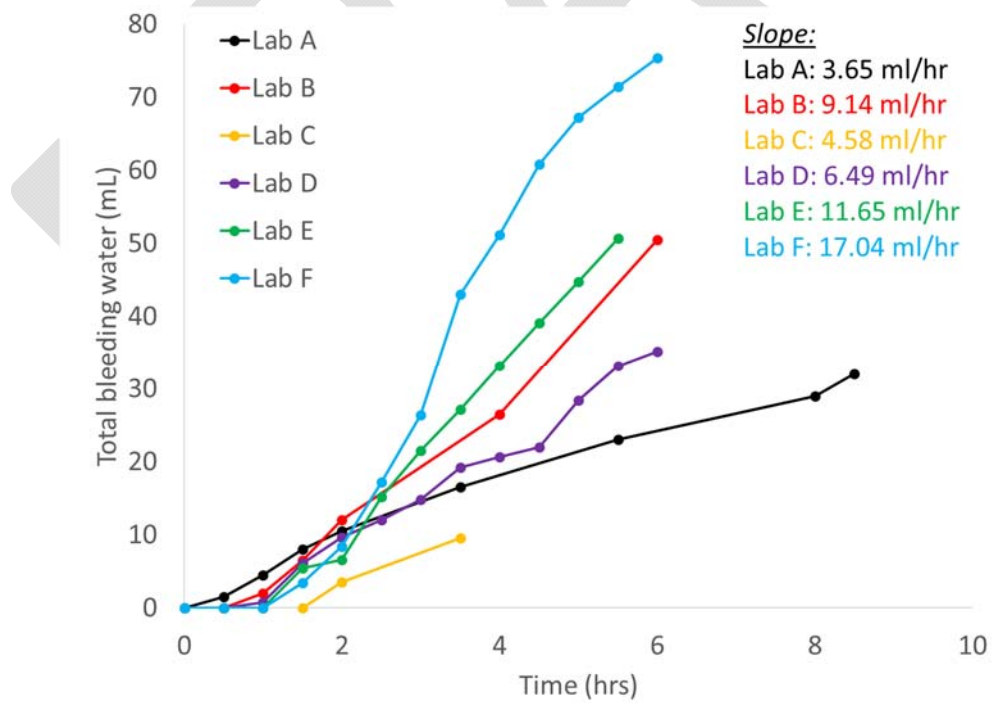


Figure 2. Bleeding as a function of time for mixtures A to F, determined at 30 min intervals. The average slope of the lines are shown in the upper right corner.

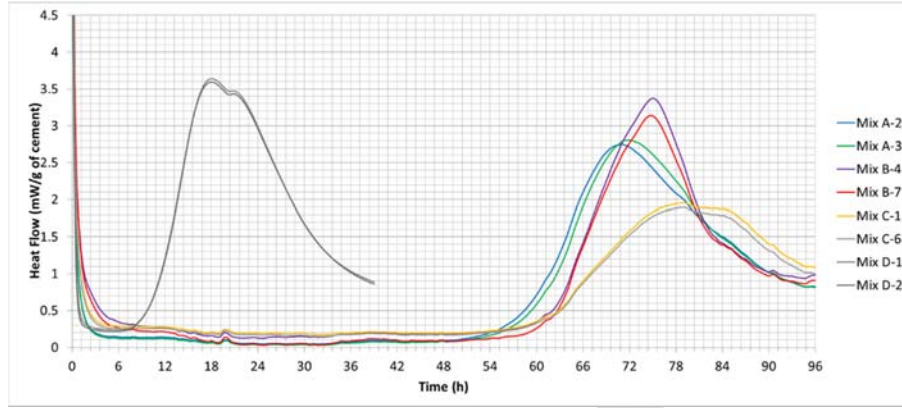


Figure 3. Isothermal calorimeter profiles of the reproduced pastes for mix designs A to D. All mixtures were measured in pairs of two samples.

3.4 Time evolution of workability and rheological parameters

Table 8 shows the evolution of workability (slump flow and L-box) and rheological properties over time. It should however be noted that the rheological data obtained for mix design D are doubtful due to excessive plug flow. The measurement results at 4 and 6 hrs are not included in the table, as the sheared zone was substantially smaller than the largest aggregate, indicating the measurement was not performed on concrete, but on a mortar layer. The results at 0 and 2 hrs are also showing substantial particle migration.

Figure 4 and Figure 5 show the relationship between slump flow and yield stress, and slump flow speed and plastic viscosity, respectively. The slump flow speed was calculated based on the T_{50} for mixtures A and B, and on T_{final} for mixtures D, E and F. The obtained lab results are compared to the relationships obtained from the European tests. Differences can be attributed to some differences in the rheometer and the interpretation, but can also be due to different materials, the slump flow test and the mixing energy. Also, no relationship was found between the slump flow speed of mixtures E and F, and the plastic viscosity measured with the ICAR rheometer. Examining the European curve shows a similar results in a similar range of slump flow speeds: the European curve is almost horizontal as well.

Figures 6 to 9 show the time evolution of the slump flow, L-box filling ratio (H_2/H_1), yield stress and viscosity, respectively. It can be seen that mixture D has the lowest slump flow retention, which may be attributed to the use of recycled water in the field, but not in the lab. It can also be seen in Figure 6 to Figure 8 that the yield stress or slump flow retention is substantially different for different mixtures: Mixtures A, C and D lose slump flow over time, mixtures E and F remain approximately constant, and mixture B shows a significant increase. Slump flow, L-box filling ratio and the dynamic yield stress results deliver similar conclusions, hence only one assessment of yield stress is necessary. For all mixtures, the plastic viscosity shows minor variations with time (Figure 9) (especially compared to “standard” SCC results, used in structures other than deep foundations).

Table 8. Evolution of fresh properties over time. The rheological measurements on mixture D are doubted.

TEST METHOD	AGE	PROD. A	PROD. B	PROD. C	PROD. D	PROD. E	PROD. F
SLUMP FLOW (MM/IN.)	0 hr	622 / 24.5	489 / 19.25	616 / 24.25	493 / 19.4	410 / 16.1	460 / 18.1
	2 hr	578 / 22.75	533 / 21.0	505 / 20.0	305 / 12.0	415 / 16.3	483 / 19.0
	4 hr	533 / 21.0	641 / 25.25	413 / 16.25	105 / 4.15 (slump)	425 / 16.7	543 / 21.4
	6 hr	476 / 18.75	603 / 23.75	368 / 15.5	-	385 / 15.2	493 / 19.4
T50 OR TFINAL (S)	0 hr	8.0 (T ₅₀)	3.9 (T ₅₀)	-	6.7 (T _{final})	2.7 (T _{final})	6.3 (T _{final})
	2 hr	11.9 (T ₅₀)	4.5 (T ₅₀)	-	2.8 (T _{final})	2.3 (T _{final})	10.3 (T _{final})
	4 hr	17.1 (T ₅₀)	3.9 (T ₅₀)	-	-	2.3 (T _{final})	7.0 (T _{final})
	6 hr	-	4.0 (T ₅₀)	-	-	1.7 (T _{final})	6.6 (T _{final})
YIELD STRESS (PA)	0 hr	23	113	11	173	173	133
	2 hr	14	44	43	319	183	60
	4 hr	30	21	102	-	175	32
	6 hr	30	26	138	-	162	35
PLASTIC VISCOSITY (PA S)	0 hr	85	21	54	8	21.4	19.2
	2 hr	93	44	59	10	46.9	43.1
	4 hr	76	39	53	-	34.9	47.4
	6 hr	73	35	48	-	30.6	44.7
L-BOX H2/H1 (%)	0 hr	26	39	57	-	-	-
	2 hr	15	33	26	-	-	-
	4 hr	0	65	0	-	-	-
	6 hr	0	48	0	-	-	-
L-BOX FLOW TIME (S)	0 hr	22.0	3.1	3.1	-	-	-
	2 hr	28.5	5.6	9.2	-	-	-
	4 hr	-	4.1	-	-	-	-
	6 hr	-	7.4	-	-	-	-

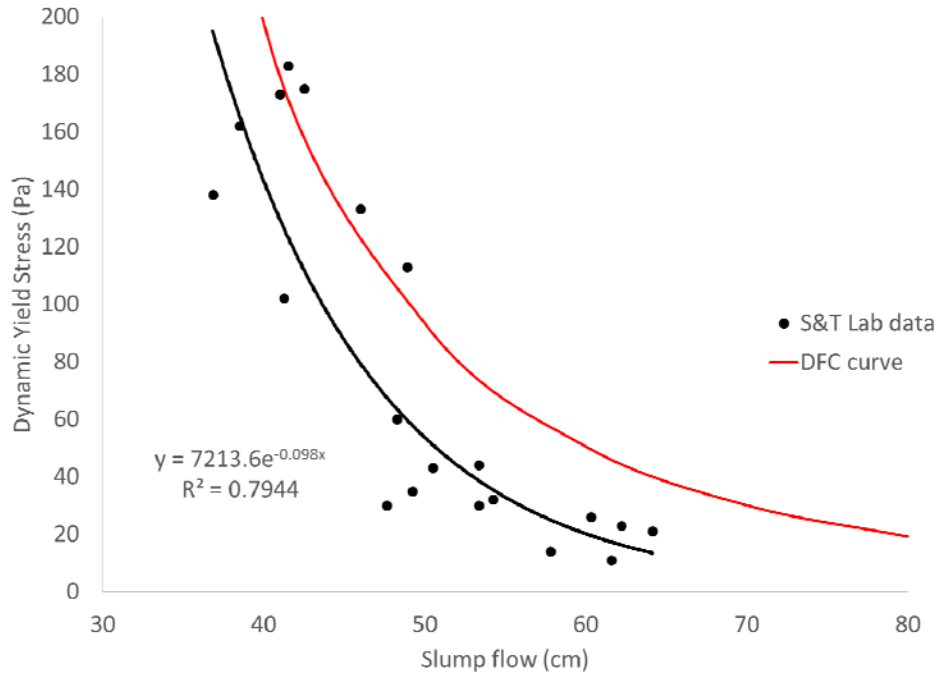


Figure 4. Relationship between yield stress and slump flow (in cm), based on the results for mixtures A, B, C, E and F. The black data are the US lab results, while the red curve was established based on European data.

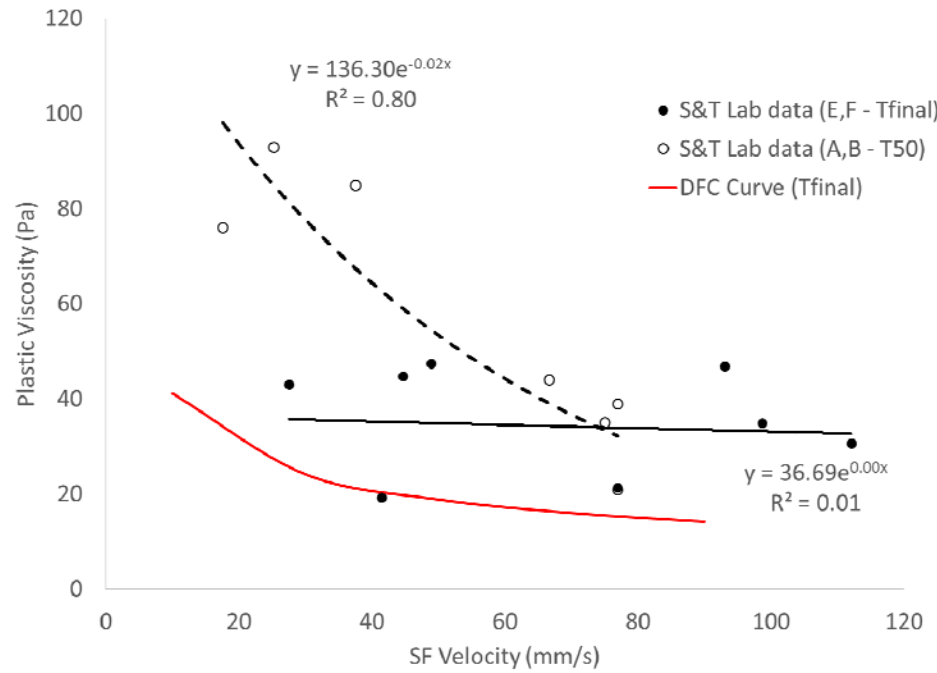


Figure 5. Relationship between slump flow speed, calculated based on T_{final} for mixtures E and F, and calculated based on T_{50} for mixtures A and B, and the viscosity. The black data are the US lab results, with E and F being the full dots and full black line, and A and B represented by the hollow dots and the dashed line. The red curve stems from the European tests.

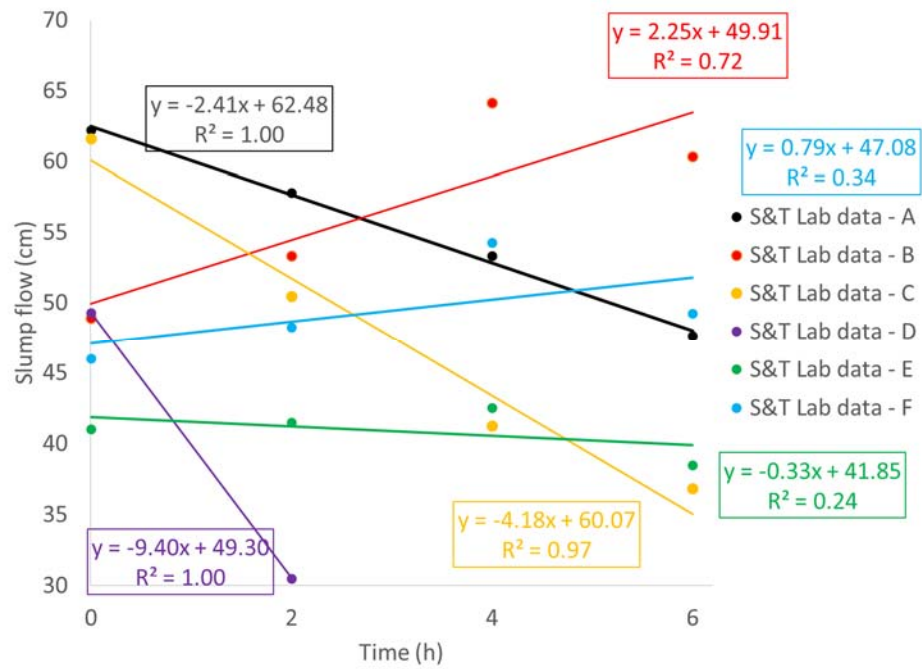


Figure 6. Slump flow retention for all mixtures.

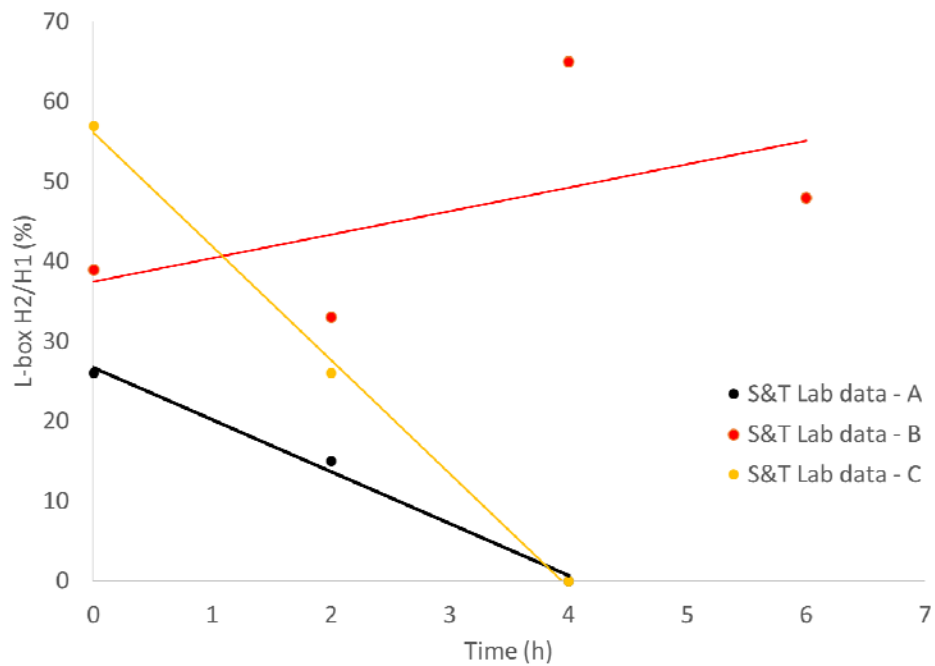


Figure 7. L-box H2/H1 retention, for mixtures A, B and C.

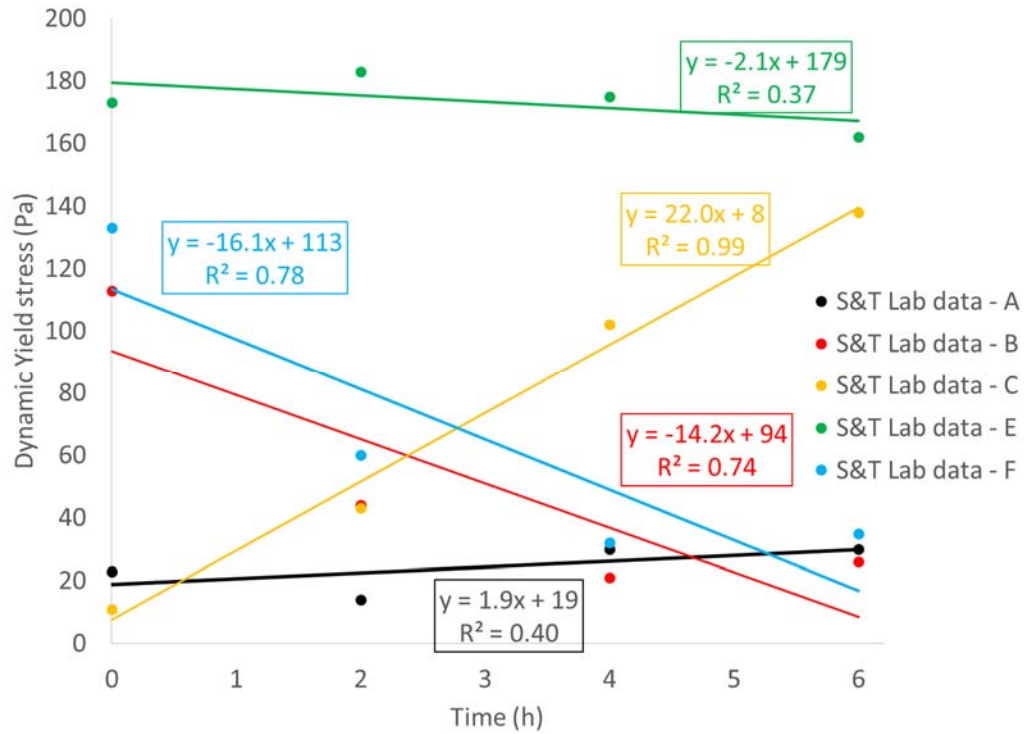


Figure 8. Dynamic yield stress retention for all mixtures, except for producer D.

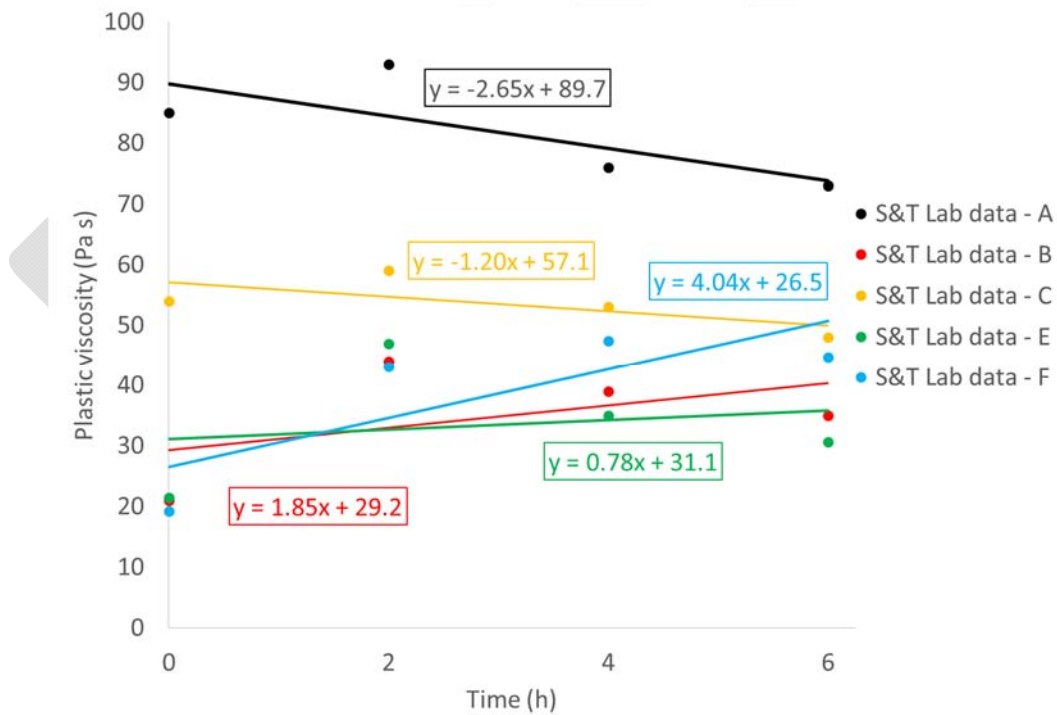


Figure 9. Plastic viscosity retention for all mixtures, except for producer D.

3.5 Thixotropy

The thixotropic properties are assessed by means of rheology in two ways. The ICAR rheometer can be used to determine the static yield stress, by rotating the vane at low speed (0.025 rps), while registering the torque value. Once a maximum in torque value is observed, the test is stopped. This maximum value can be transformed into static yield stress. The portable vanes use a similar procedure, but the samples remain fully undisturbed until testing, while some disturbance occurs in the repeated testing with the ICAR rheometer, which in fact lowers the slope of the curve. This disturbing effect can be seen when comparing the static yield stress measurements during the first 2 min (see

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Table 9) Portable vanes of different dimensions are inserted once the square buckets are filled with fresh concrete, and a manual torque-meter registers the maximum torque needed to rotate the vane slowly for 90 degrees.

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Table 9 shows the results of the tests executed to characterize the thixotropic properties of the mixtures. For the slump flow and L-box tests, two measurements were performed consecutively: one where the test was performed immediately after filling the equipment, and one in which the sample was at rest for four minutes in the molds before performing the test. The static yield stress increase with time was monitored with the ICAR rheometer over a 10 min time period (Figure 10), and with the portable vanes over one hour (Figure 14). In

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Table 9, the slope as a function of time for each property was also determined.

Figure 10 indicates that mix design D shows no thixotropic properties, while mixtures B, C, E, A, and F are ranked with increasing thixotropy. The slope of the lines in Figure 10 is used as a characteristic of thixotropy. The change in slump flow with time due to a resting time shows an opposite correlation with the thixotropy, which is illogical (Figure 11). The changes in L-box filling (Figure 12) ratio and L-box filling time (Figure 13) induced by a resting time show a logical relationship with thixotropy, but the increase in filling ratio for mixtures B and C, and the decrease in filling time for mixture B do not make sense. Although successful results for such methods are reported in literature, a lack of accuracy in the slump flow and L-box measurements renders them not suitable for the assessment of thixotropy in the field.

The portable vane measurements reflect approximately the thixotropy measured with the ICAR rheometer, although the no-thixotropy of mixture B is remarkable. It can be argued that the workability increase in mixture B could counter the thixotropic development, as the portable vane time-span is 60 min, compared to the ICAR thixotropy assessment (10 min). However, following the same argumentation, mixture D should show an increase in static yield stress with time, as it has a substantial workability loss and shows no thixotropy. This increase is not observed, which could indicate that the workability loss only starts after 1 hr, but the research team has no certainty on this statement.

Table 9. Test results for thixotropy. For each test, all raw data are included and a slope is determined as the change in property per minute or per second.

TEST METHOD	AGE	PROD. A	PROD. B	PROD. C	PROD. D	PROD. E	PROD. F
SLUMP FLOW (MM/IN.) OR (MM/MIN / IN./MIN)	0 min	648 / 25.5	502 / 19.75	610 / 24.0	-	-	-
	4 min	648 / 25.5	492 / 19.38	603 / 23.75	-	-	-
	Slope	0 / 0	2.35 / 0.0925	1.59 / 0.0625	-	-	-
L-BOX H2/H1 (%) OR (%/MIN)	0 min	23	31	57	-	-	-
	4 min	7	43	64	-	-	-
	Slope	4.0	-3.0	-1.75	-	-	-
L-BOX FLOW TIME (S) OR (S/MIN)	0 min	31	5.0	3.6	-	-	-
	4 min	43	3.8	3.8	-	-	-
	Slope	3.0	-0.3	0.05	-	-	-
STATIC YIELD STRESS (ICAR) (PA) OR (PA/S)	0 s	67	199	266	270	537	380
	30 s	111	217	323	315	573	434
	60 s	111	217	341	297	573	425
	120 s	183	226	395	297	564	469
	240 s	228	253	422	261	626	559
	600 s	443	361	547	306	842	1026
	Slope	0.603	0.262	0.418	0.014	0.493	1.061
STATIC YIELD STRESS (PORTABLE VANE) (PA) OR (PA/MIN)	0 min	539	604	259	517	775	745
	15 min	1065	533	533	692	1324	1908
	30 min	2383	701	631	491	2296	2415
	60 min	2917	604	1006	604	3626	4387
	Slope	41.3	0.6	11.9	0.4	48.6	59.0

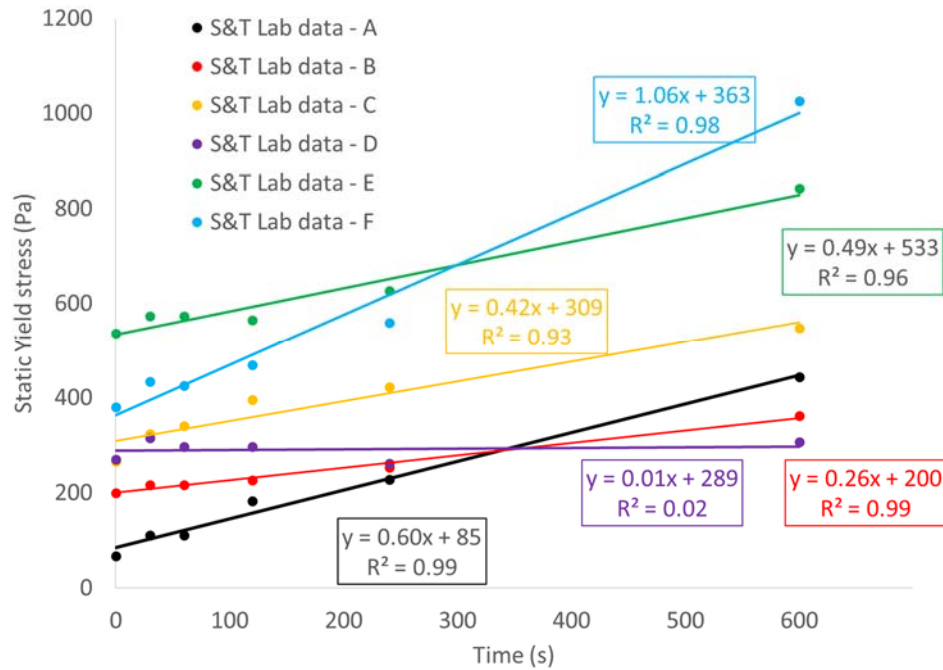


Figure 10. Static yield stress, determined with the ICAR rheometer, as a function of time.

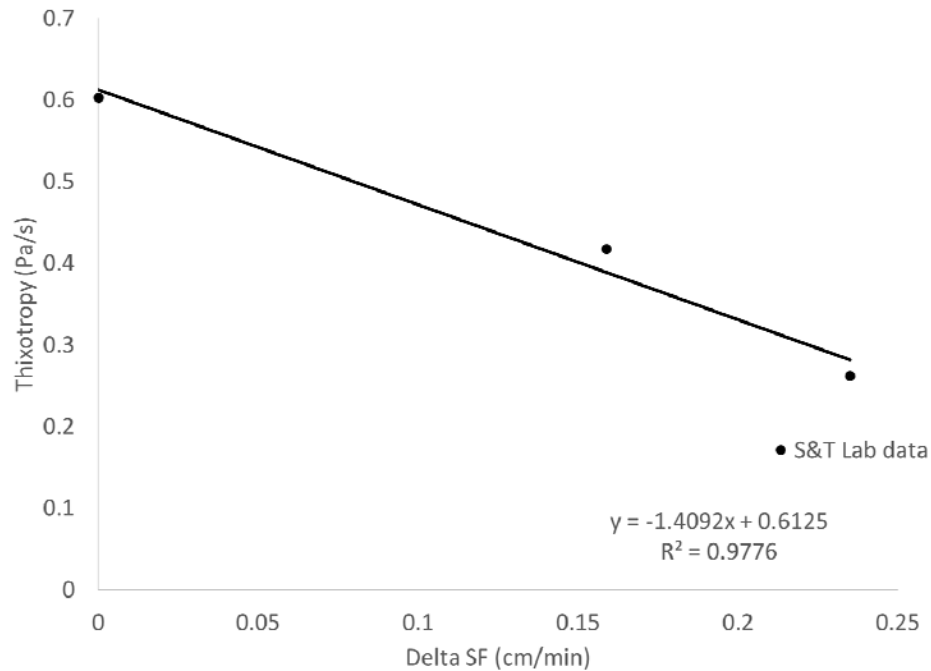


Figure 11. The change in slump flow due to 4 min resting (expressed as the slump flow difference divided by time), as a function of the static yield stress increase with time. Results only obtained for mixtures A, B and C.

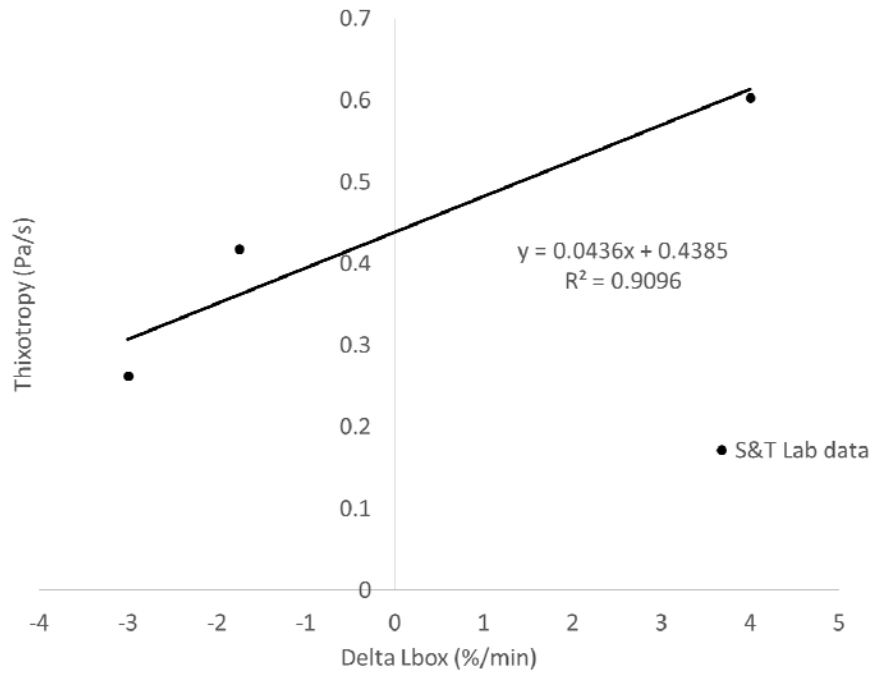


Figure 12. Change in L-box filling ratio ($H2/H1$) with increased resting time as a function of the increase in static yield stress. Results only obtained for mixtures A, B and C.

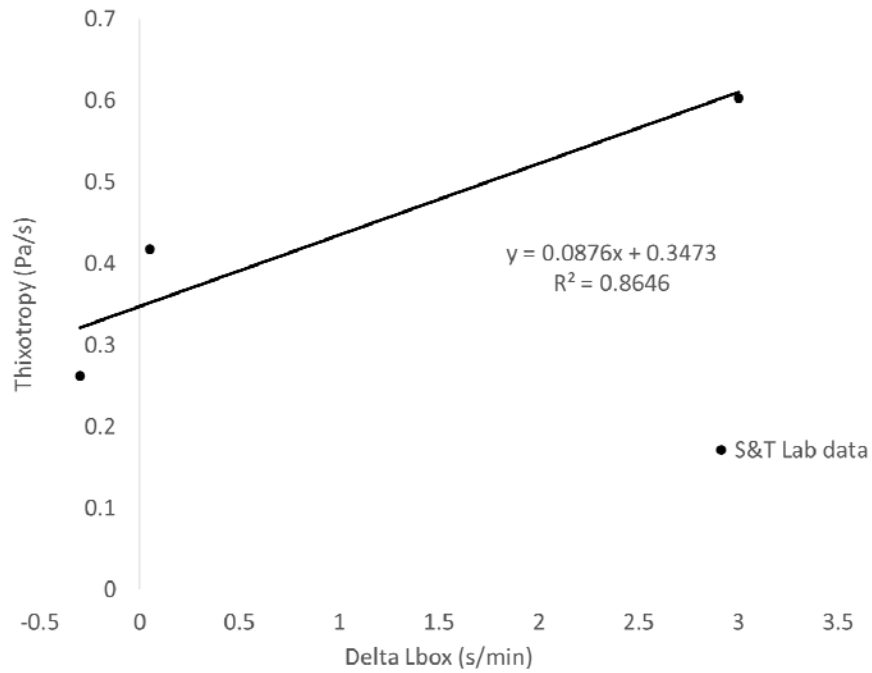


Figure 13. Change in L-box flow time due to resting as a function of the increase in static yield stress. Results only obtained for mixtures A, B and C.

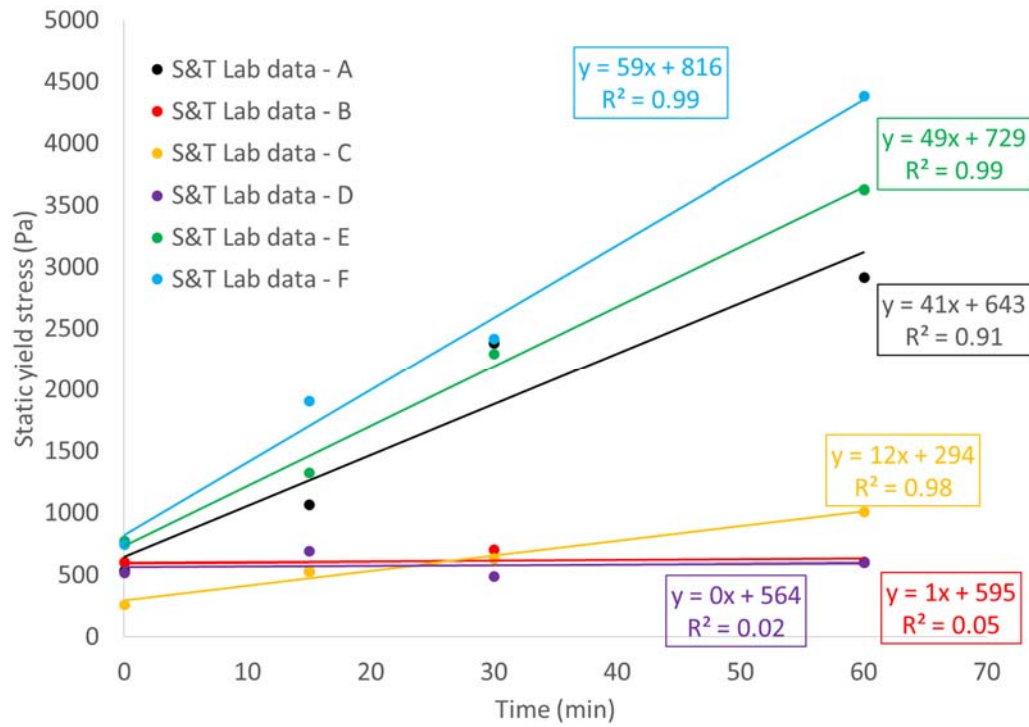


Figure 14. Increase in static yield stress measured by portable vane as a function of resting time.

4 Comparing US Lab and Field Tests

In this section, the results from the laboratory are compared to the results reported in the field tests. The following test results are compared:

- Slump flow at 0, 2, 4, and 6 hrs
- L-box filling height (H2) at 0 hrs (for mixtures A, B and C)
- L-box filling time at 0 hrs (for mixtures A, B and C)
- Static Stability by means of the column segregation test
- Total % bleeding
- Bleeding rate
- Total expelled water from the Filter press

It should be kept in mind that the research team has made an attempt to replicate the mix designs as good as possible, but that some deviations were introduced, described in section 2 of this report.

Figure 16 shows the results of the column segregation tests, showing some differences for mixtures B, C and E. The sieve stability results for the lab test of producers D, E and F are also included. Despite the variations, all mixtures showed adequate static stability, if a maximum criterion for the column segregation test is established at 15%. Figure 17 shows the total percentage of bleeding, calculated according to ASTM C232, relating the amount of bleed water to the total amount of water in the concrete in the container. All lab and field results look more or less similar. Figure 18 shows the bleeding rate for all mixtures evaluated, where conclusions on comparison are hard to draw seen the lack of field data for producers D and E, and the fact that the field mixture of producer C was reported to show no bleeding. It seems, for the data available, that the bleeding rate was slightly higher for the lab specimens than for the field evaluations. Figure 19 shows the detailed bleeding rates for all mixtures from producer B. Figure 20 shows the Bauer filter press results, in which the lab data are systematically higher than the field data.

Table 10 to 12 show the comparison between the lab tests for producers A, B, C, D, E and F. It should be noted that producer B delivered multiple field testing reports for different sites. The B field 1 mixture from producer B is the mix design evaluated in the laboratory (although this was unknown to the research team until after the tests). Other mixtures are slightly different. Mixture B field 5 was a strongly altered mix design for a field trial, and it was reported to have insufficient workability retention, and therefore could not be used as a concrete suitable for deep foundations. Tests on integrity received from DFI showed that only mixture B Field 1 had integrity issues. All other B mixtures and the field tests for producer A and C resulted in adequate integrity of the foundations. No information is available on the integrity of the field test of producer D.

From the data in Figure 16 shows the results of the column segregation tests, showing some differences for mixtures B, C and E. The sieve stability results for the lab test of producers D, E and F are also included. Despite the variations, all mixtures showed adequate static stability, if a maximum criterion for the column segregation test is established at 15%. Figure 17 shows the total percentage of bleeding, calculated according to ASTM C232, relating the amount of bleed water to the total amount of water in the concrete in the container. All lab and field results look more or less similar. Figure 18 shows the bleeding rate for all mixtures evaluated, where conclusions on comparison are hard to draw seen the lack of field data for producers D and E, and the fact that the field mixture of producer C was reported to show no bleeding. It seems, for the data available, that the bleeding rate was slightly higher for the lab specimens than for the field evaluations. Figure 19 shows the detailed bleeding rates for all mixtures from producer B. Figure 20 shows the Bauer filter press results, in which the lab data are systematically higher than the field data.

Table 10 to 12, several figures were created comparing the lab and field properties of the mixtures. Figure 15 compares the slump flow of the lab results (full black dots in Fig. 15) and the corresponding field concretes (full red dots in Fig. 15). The hollow red dots represent the well-performing alternative mixtures from producer B, while the green-red triangle shows the bad result (B Field 5). On the X-axis, the producers are numbered 1 to 6 instead of A to F. It can be seen in Figure 15 that the slump flow of the mixtures in the field is similar to the slump flow in the lab, apart from a small deviation for mix design C.

Figure 16 shows the results of the column segregation tests, showing some differences for mixtures B, C and E. The sieve stability results for the lab test of producers D, E and F are also included. Despite the variations, all mixtures showed adequate static stability, if a maximum criterion for the column segregation test is established at 15%. Figure 17 shows the total percentage of bleeding, calculated according to ASTM C232, relating the amount of bleed water to the total amount of water in the concrete in the container. All lab and field results look more or less similar. Figure 18 shows the bleeding rate for all mixtures evaluated, where conclusions on comparison are hard to draw seen the lack of field data for producers D and E, and the fact that the field mixture of producer C was reported to show no bleeding. It seems, for the data available, that the bleeding rate was slightly higher for the lab specimens than for the field evaluations. Figure 19 shows the detailed bleeding rates for all mixtures from producer B. Figure 20 shows the Bauer filter press results, in which the lab data are systematically higher than the field data.

Table 10. Lab and field data for producers A, C and D

TEST METHOD	UNIT	PROD. A		PROD. C		PROD. D	
		Lab	Field	Lab	Field	Lab	Field
INITIAL SLUMP FLOW	(mm/in)	622 / 25.5	493 / 19.5	616 / 24.25	489 / 19.25	493 / 19.4	476 / 17.75
SF AT 2 HRS	(mm/in)	578 / 22.75	540 / 21.25	505 / 19.87	400 / 15.75	305 / 12.0	298 / 11.75
SF AT 4 HRS	(mm/in)	533 / 21.0	425 / 16.75	413 / 16.25	292 / 11.50*	105 / 4.15*	210 / 8.27*
SF AT 6 HRS	(mm/in)	476 / 18.75	356 / 14.0	368 / 14.5	130 / 5.11*	-	-
COLUMN SEGREGATION	(%)	7.4	3.1	13.5	1.2	8.7	7.4
BLEEDING	(%)	1.72	1.5	0.45	0	1.73	-
BLEEDING RATE	(ml/hr)	3.65	3.37	4.58	0	6.49	-
BAUER FILTER PRESS	(ml)	30.1	-	25.3	18	43	33
L-BOX H2	(mm)	42.5	56	62.7	31	-	-
L-BOX FLOW TIME	(s)	22	-	3.6	6.2	-	-

*slump

Table 11. Lab and field data for producers E and F

TEST METHOD	UNIT	PROD. E		PROD. F	
		Lab	Field	Lab	Field
INITIAL SLUMP FLOW	(mm/in)	410 / 16.1	451 / 17.8	460 / 18.1	476 / 18.7
SF AT 2 HRS	(mm/in)	415 / 16.3	356 / 14.0	483 / 19.0	533 / 21.0
SF AT 4 HRS	(mm/in)	425 / 16.7	311 / 12.2	543 / 21.4	572 / 22.5
SF AT 6 HRS	(mm/in)	385 / 15.2	286 / 11.3	493 / 19.4	508 / 20.0
COLUMN SEGREGATION	(%)	6.8	1.9	-	5.3
BLEEDING	(%)	2.2	4.8	3.0	1.4
BLEEDING RATE	(ml/hr)	11.6	-	17.0	4.3

BAUER PRESS	FILTER	(ml)	41.1	35	40.7	31
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Table 12. Lab and field data for producer B. Note that the field 5 test reflects an unsuitable mixture for deep foundations.

TEST METHOD		UNIT	PROD. B					
			Lab	Field 1	Field 2	Field 3	Field 4	Field 5
INITIAL SLUMP FLOW	(mm/in)		489 / 19.25	394 / 15.5	600 / 23.6	489 / 19.25	470 / 18.5	394 / 15.5
SF AT 2 HRS	(mm/in)		533 / 21.0	464 / 18.25	635 / 25.0	584 / 23.0	508 / 20.0	362 / 14.25
SF AT 4 HRS	(mm/in)		641 / 25.25	470 / 18.5	616 / 24.25	622 / 24.5	533 / 21.0	349 / 13.75
SF AT 6 HRS	(mm/in)		603 / 23.75	413 / 16.25	450 / 17.75	597 / 23.5	451 / 17.75	318 / 12.5
COLUMN SEGREGATION	(%)		4.1	10.3	5.7	5.2	5.9	0
BLEEDING	(%)		2.56	3.69	10.41	5.8	2.85	0
BLEEDING RATE	(ml/hr)		9.14	1.39	14.30	13.64	1.87	0
BAUER FILTER PRESS	(ml)		49.4	25	-	-	27	36
L-BOX H2	(mm)		44.5	40.9	-	-	-	-
L-BOX FLOW TIME	(s)		3.0	1.0	-	-	-	-

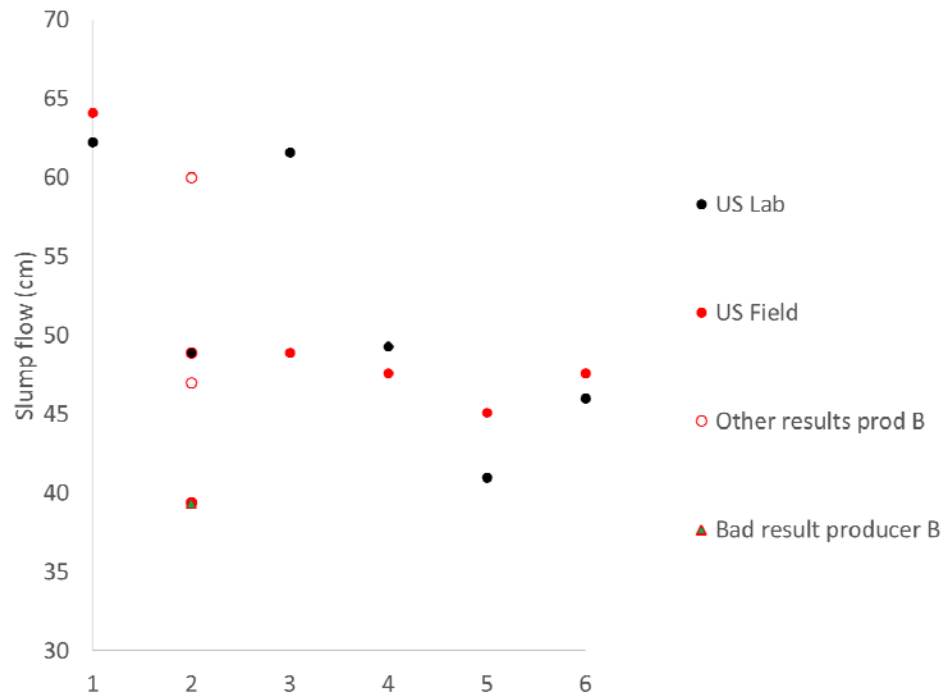


Figure 15. Comparison of slump flow between lab (black) and field (red) for producers A to F, numbered 1 to 6 in the graphs. Individual results are also shown for producer B, including mixture B Field 5, labeled as “bad result”.

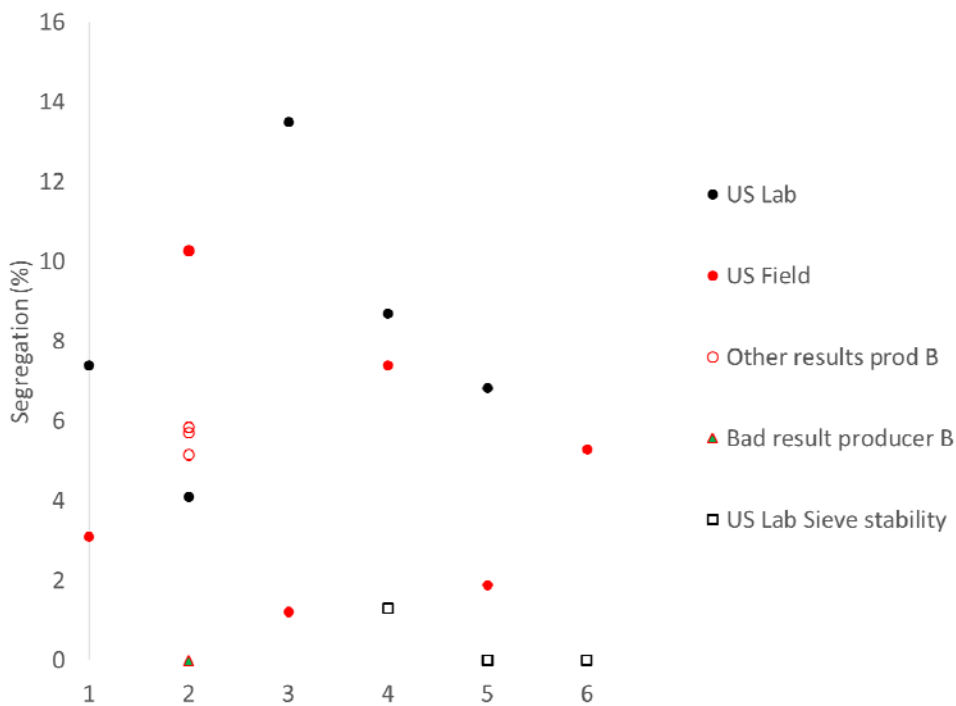


Figure 16. Comparing of static segregation (column segregation test, unless indicated otherwise) between lab and field.

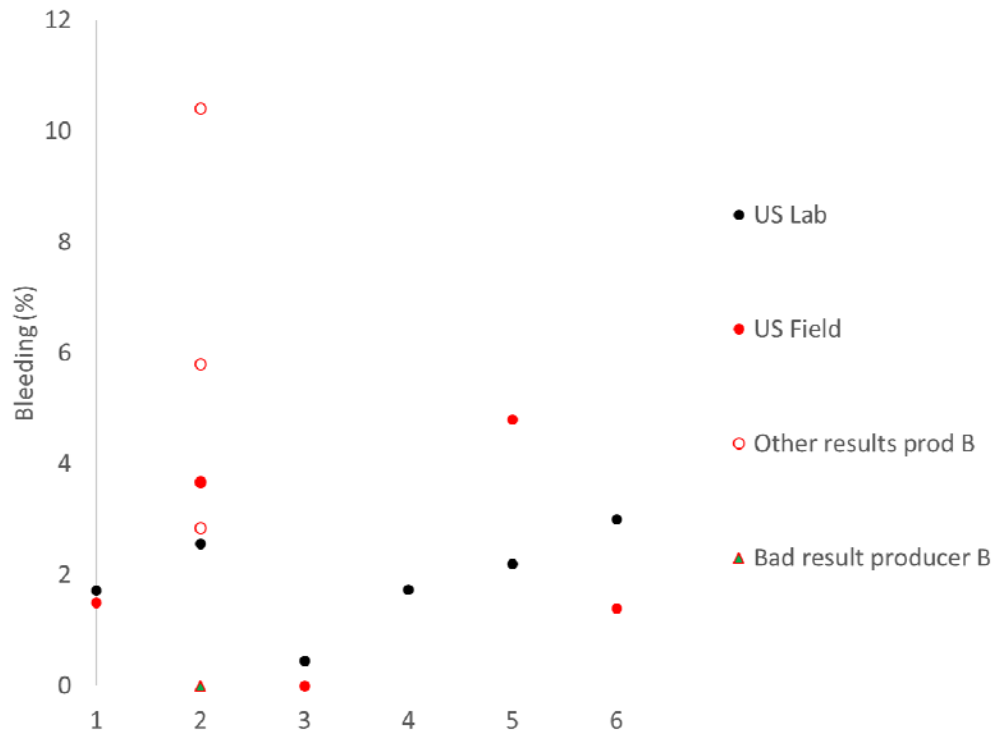


Figure 17. Comparing total % bleeding for all mixtures.

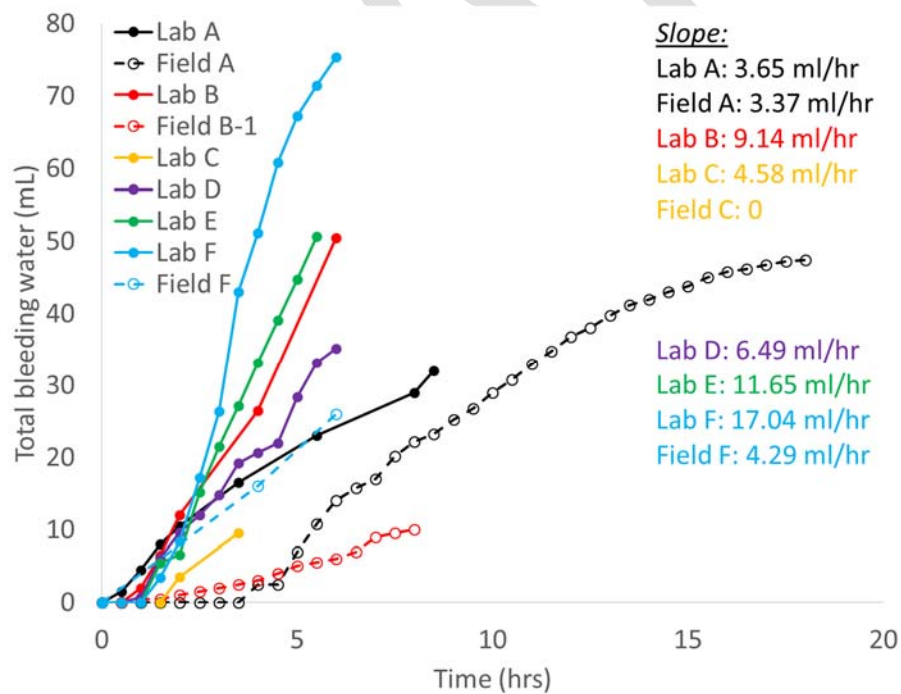


Figure 18. Comparison of bleeding rate for all mixtures.

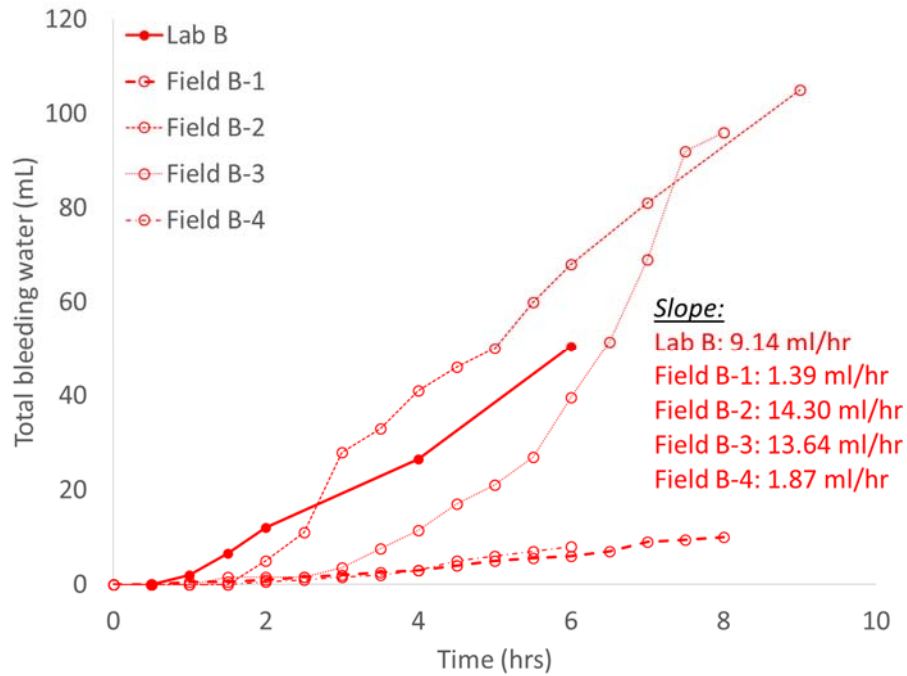


Figure 19. Detailed bleeding rate for lab mix B and the four mixtures from producer B in the field.

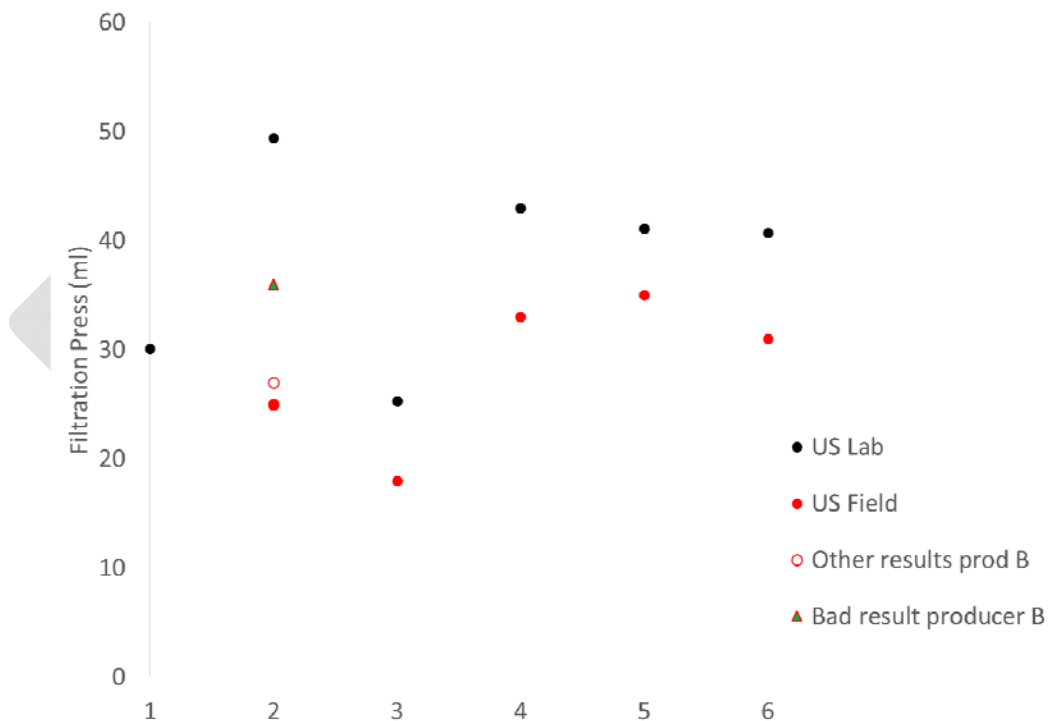


Figure 20. Bauer filter press results from lab and field tests.

Figure 21 shows the slump flow retention of all lab mixtures with the field counterparts. Note that when slump flow values of 300 mm (30 cm) or lower are reported, that these values correspond to the slump instead of the slump flow. As can be seen in Figure 21, the slump flow retention of the lab mixtures is always slightly better than the retention of the field mixtures. Potential causes can be found in covering the sample to prevent

evaporation of water, or a difference in mixing energy prior to starting the tests at 2, 4 and 6 hrs. The mixtures in the laboratory were remixed in the drum mixtures, while for the field measurements, it is suspected that the remixing was performed by hand. Figure 22 shows the slump flow retention for all mixtures from producer B separately. In general though, it can be concluded that lab and field measurements showed similar trends in slump flow retention.

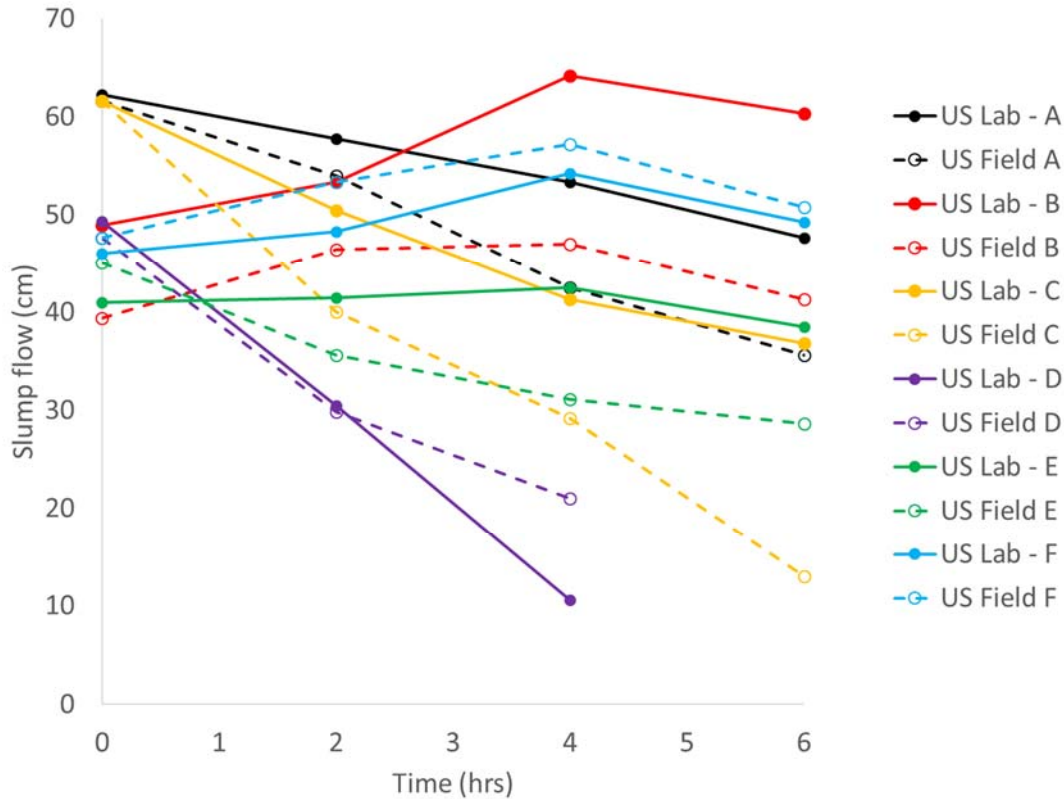


Figure 21. Slump retention for the lab samples, compared to their respective field tests. Note that when a slump flow lower than 30 cm, this value represents the slump of the concrete.

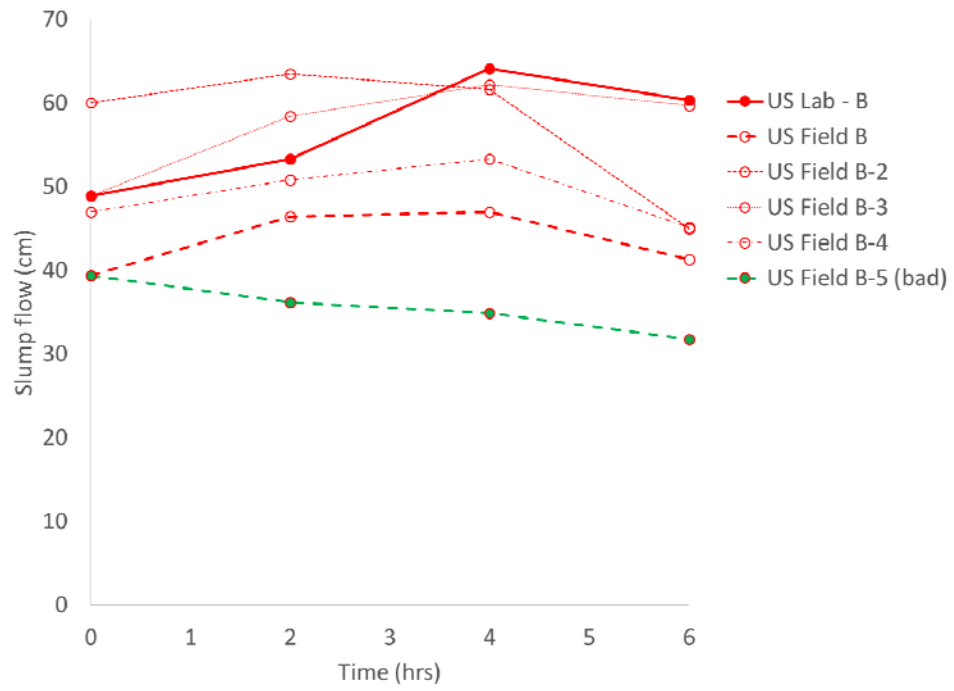


Figure 22. Slump flow retention for all mixtures from Producer B

5 Summary

Six concrete mixtures with materials from six different concrete producers were evaluated in the lab. The objective of this testing program is to duplicate the mixtures and link fresh concrete properties to rheology. As discussed in Miami (April 2017) and Zurich (July 2017), a testing protocol is proposed, for which DFI and EFFC may determine acceptance criteria. From the test results, the following can be concluded:

- For the reproduction of the concrete in the lab, the dosage of WRA and/or HRWRA was altered to obtain a slump flow similar to the field. Some large differences in admixture dosage have been noted, showing the influence in fresh properties of different factors, including but not limited to: mixing energy, moisture content of the aggregates, use of recycled water in the field, and testing procedure, tools, and temperature.
- Decent correlations between dynamic yield stress and slump flow were obtained, approaching the European data.
- A good correlation between viscosity and slump flow speed, calculated as $300/T_{50}$ (mm/s), is obtained. However, for the slump flow speed data calculated based on T_{final} , no correlation with the viscosity was found. Even in the European data, for the range of slump flow speeds measured, the relationship between viscosity and the slump flow speed is nearly horizontal.
- 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.
- The viscosity has been found to vary minimally over time, as expected.
- 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.
- Using the difference in slump flow or L-box filling ratio, taken from an initial and a delayed measurements, does not deliver adequate indicators for thixotropic build-up at rest. Hence, it was suggested to remove these measurements.
- Static stability results show that all mixtures are stable (column segregation value < 15%). The lab results are in line with the field data.
- The total % bleeding of the mixtures evaluated in the lab corresponds well to the values reported in the field. Bleeding rate data were also derived.
- 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, and on the results from TUMunich, the following recommendations were developed for test methods for deep foundation concrete:

- 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.

6 Acknowledgments

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