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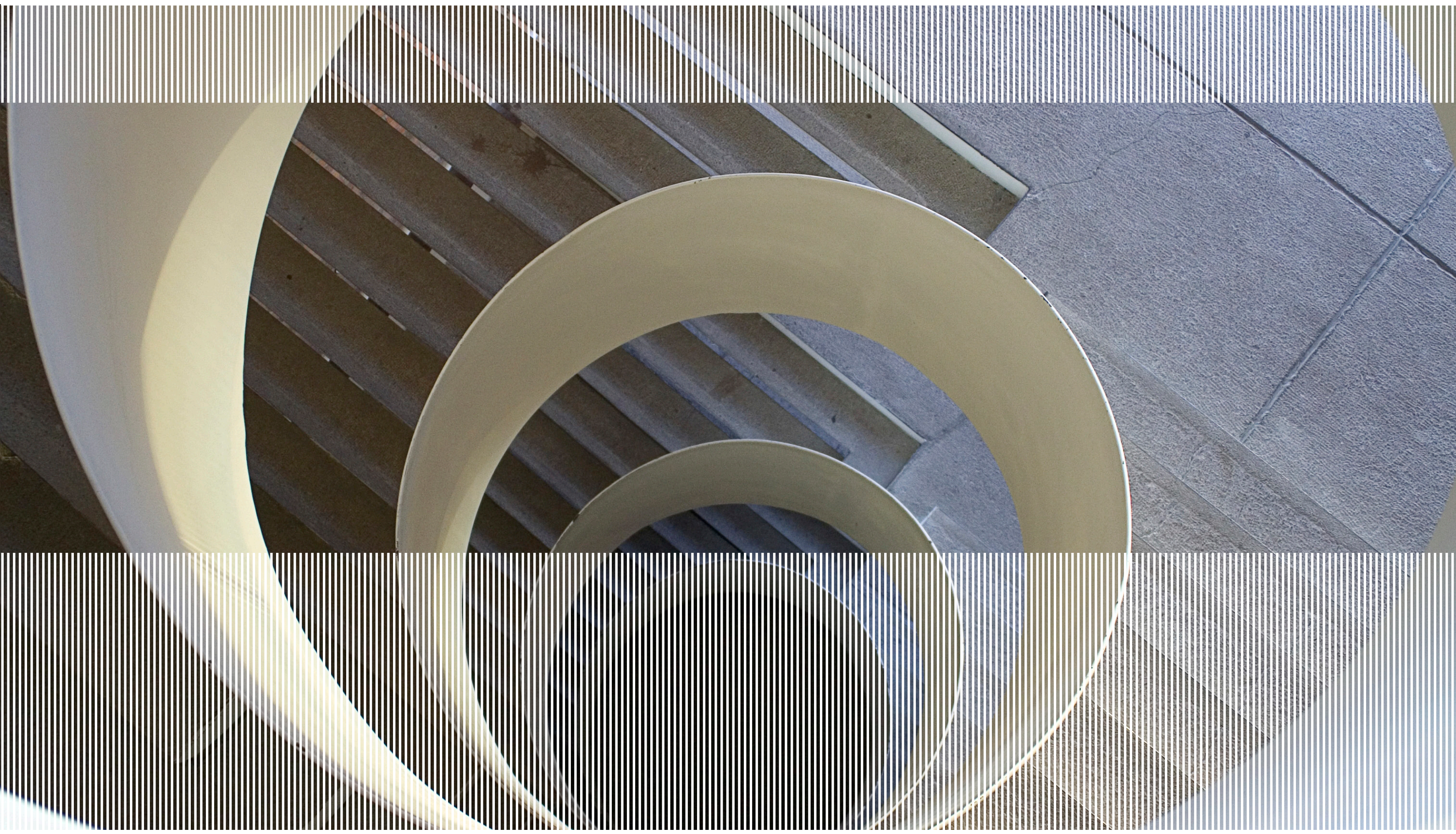
Stability of SCC – robustness for changes in water content and sand grading

COIN Project report 47 – 2013



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FA 2 Competitive constructions

SP 2.1 Robust highly flowable concrete

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Preface

This study has been carried out within COIN - Concrete Innovation Centre – one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfil this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology – NTNU (research partner) and industry partners, 15 – 20 PhD-students, 5 – 10 MSc-students every year and a number of international guest researchers, work on presently eight projects in three focus areas:

- Environmentally friendly concrete
- Economically competitive construction
- Aesthetic and technical performance

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %).

For more information, see www.coinweb.no

Tor Arne Martius-Hammer
Centre Manager

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APPENDICES

1 Introduction

Concrete producers experience occasionally unintended variation of the water content as well as the sand grading in daily production of concrete. The purpose of the study reported here was to investigate how such variations may influence the stability of SCC. This was done as a robustness test on laboratory scale, with controlled variation of the water content (target: +/- 15 litre/m^3) and sand grading (three variations of the 0-2 mm fraction) in an ordinary Norwegian concrete for house building (NS-EN 206-1 M60B30). The stability was measured according to four methods: visual segregation index, rheological segregation index, sieve segregation index and visual analyses of sawn hardened cylinders. In addition, the results were supported by flow resistance measurements and stability measurements of the equivalent matrices (the sum of cement, fines of sand (< 0,125 mm), superplasticiser and water), according to the Particle-Matrix-Model.

2 Experimental

2.1 Mix design basis

The idea was to study three concretes with three different sand grading and three different water contents, the latter by adding or subtracting 15 litres of water to/from each of these concretes. This gives virtually a total of 9 concretes. However, as the two first "Minus" concretes showed quite poor stability, it was decided to not perform the one with the highest water content (assuming to give even poorer stability). An overview of mixes is shown in Table 1. The target slump flow was 675 mm for all concretes.

Different gradings were achieved by combining sands; a fine crushed sand 0-2 mm and a coarse naturally rounded sand 0-8 mm. The grain size distributions of the sands are given in Fig 1. The combination was done in such a way that the matrix content varied in steps of 15 litres (a reference concrete and two concretes with +/- 15 litre of matrix, respectively). The 15 litres of water was added/subtracted without changing the cement content, resulting in a corresponding matrix change of 15 litre and a change of w/c and w/p (water/powder, powder being cement + fines of sand). Hence, the target change of matrix content of 15 litres is in the form of water or sand fines content, see also Fig 2.

In addition, a naturally rounded fine sand, rich in the 0,125-0,250 mm fraction (see Fig 1) assumed to give increased stability, was used in a fourth concrete ("Extra"). Besides the fine sand, this concrete had the same composition as the "Plus concrete" (see Table 1).

Table 1: Overview of the target matrix mix design

Concrete	Water change	Matrix content [ltr]	w/c	w/p	Cement content [kg/m^3]	Sand fines content [kg/m^3]	SP content [% of cw]-[kg/m^3]	Matrix code *)
Minus	-15	305	0,51	0,42	328	70	2,1 -7,0	wc0.51wp0.43p2.13
	0	320	0,56	0,46	328	67	1,6- 5,1	wc0.56wp0.46p1.55
Ref	-15	320	0,51	0,39	328	100	2,8 - 9,2	wc0.51wp0.39p2.80
	0	335	0,56	0,43	328	99	1,7 - 5,7	wc0.56wp0.43p1.74
	+15	350	0,61	0,47	328	98	1,2 - 4,0	wc0.61wp0.47p1.22
Plus	-15	335	0,51	0,35	328	146	3,9 - 12,9	wc0.51wp0.35p3.93
	0	350	0,56	0,39	328	143	2,5 - 8,2	wc0.56wp0.39p2.50
	+15	365	0,61	0,43	328	139	1,4 - 4,5	wc0.61wp0.43p1.37
Extra	-15	333	0,51	0,36	328	137	2,4 - 8,0	Not tested
	0	347	0,56	0,40	328	131	1,9 - 6,1	
	+15	362	0,61	0,43	328	137	1,3 - 4,2	

**) See section 2.5*

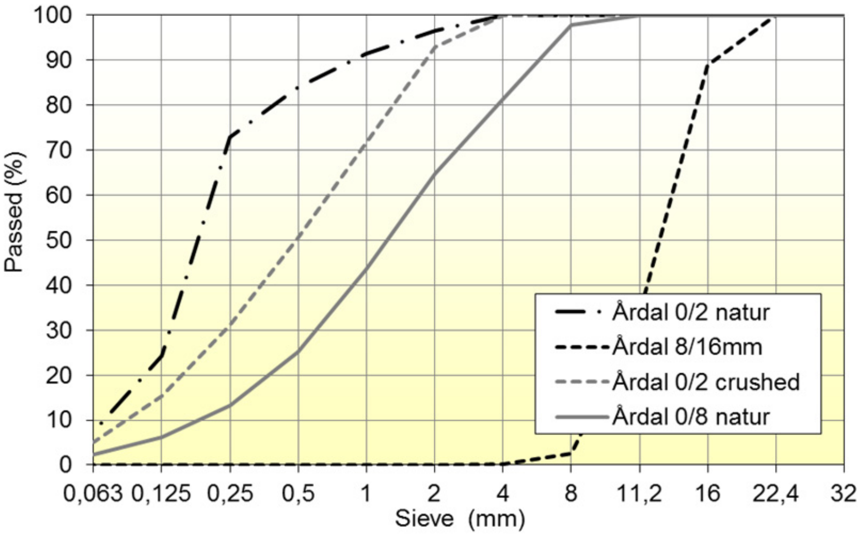


Fig. 1: Sand grading

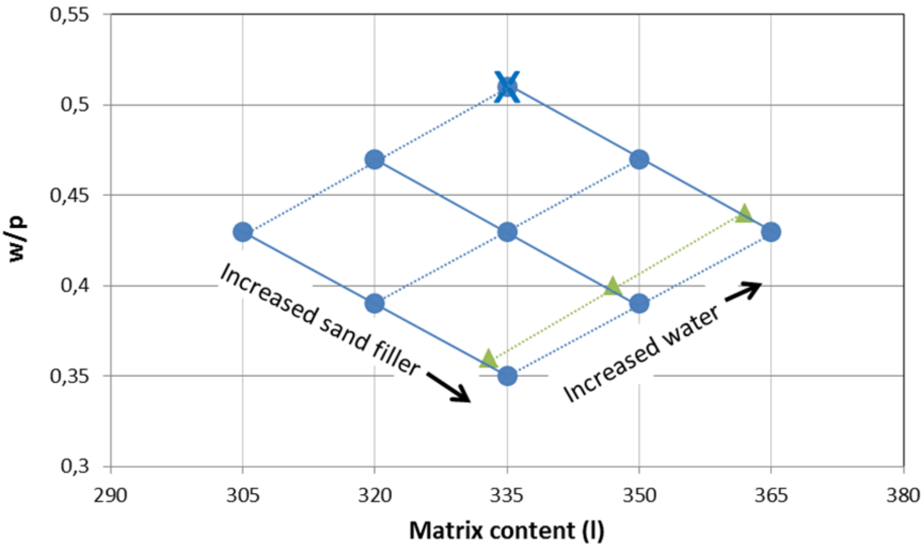


Fig. 2: Mix design approach - parameter variation (triangles represent the "Extra concrete)

The chosen parameter variation may give the following influence on stability:

Increasing the sand filler brings along:

(1) increased matrix content, contributes normally to worse stability
(2) decreased w/p, contributes to normally to improved stability (increased viscosity)
(3) increased SP content (to obtain the same slumpflow), may contribute to worse stability (reduced yield stress)

Furthermore, low w/p results in lower cement/sand fines ratio than a low w/c. Knowing that cement contributes more to stability than sand fines, this may result in less influence of w/p than if the cement/sand fines ratio was constant. Also, more sand filler brings along some more sand (0-2 mm fraction) which contributes to improved stability.

Increasing the water content gives apparently a less complicated picture: Increased matrix content and w/p (without changing the cement/sand filler ratio) both normally contributing to worse stability, and reduced SP amount normally contributing to improved stability.

Hence, the resulting effect on stability is not given. In fact, it may seem that concrete has some inherent robustness concerning "typical unintended variations in sand grading and water content".

Note that the superplasticizer content is quite high, and much higher than that recommended in some of the concretes which implies that these concretes would not been used in practice. It is uncertain how the high content influences the results.

2.2 Materials and recipes

Cement: "Norcem STD FA cement"; EN 197-1-CEM II/A-V 42.5 R Portland fly ash cement, was used in all concretes. The cement had a Blaine fineness of approx. 450 m^2/kg and density of 3010 kg/m^3.

Aggregates: "Norstone - Årdal" Gneiss/Granite aggregates of following fractions were used:

- 0-2 mm crushed sand
- 0-2 mm natural sand ("plus extra" concrete)
- 0-8 mm natural sand
- 8/16 mm partly crushed stone

Admixture: "Mapei Dynamon SX-N", acrylic polymer superplasticizer with 15 % dry solids.

The actual recipes are given in APPENDIX A.

2.3 Mixing and testing procedures of the concretes

The fresh concrete testing was performed twice; immediately after initial mixing, i.e. approximately 10 minutes after water addition, and at 60 minutes after water addition. All concrete tested at 10 min were poured back in the mixer after testing and remixed for 30 seconds with the concrete remaining in the mixer. All the remaining concrete was remixed again for 30 seconds just before testing at 60 min. The two cylinders for visual analysis of hardened concrete were cast 30-40 minutes after water addition, after 30 seconds of remixing.

All concretes were mixed in a forced pan mixer with a volume of 50 litres from Eirich. The volume of the concretes batches was 50 litres. The initial mixing procedure was:

- 1 minute dry mixing of powders and aggregates
- 2 minutes while adding mixing water and approximately the amount of superplasticizer
- 2 minutes pause/rest
- 2 minutes mixing with addition of remaining superplasticizer until target slump flow value was reached

2.4 Measurements on the concretes

2.4.1 Overview

The following measurements were performed on each of the concretes:

- Slump flow (SF) in [mm] and t_{500}, in [s] according [1], 10 and 60 minutes after water addition.
- Slump flow with J-ring (SUR) including and t_{50} in [s] and determination of Blocking Resistance (Bj) in [mm], according to [1], 10 and 60 minutes after water addition.
- Visual Segregation Index (VSI) according to [2] described below, 10 and 60 minutes after water addition.
- Rheological Segregation Index (RSI) according to [3], described below, 10 and 60 minutes after water addition.
- Sieve segregation index (SSI) according to [4], described below, 10 and 60 minutes after water addition.
- Visual segregation on cut surfaces of hardened concrete (VSHC). The method is based on [5].

Slump flow was measured first, and then all other measurements took place at the same time.

2.4.2 Slump flow with J-ring

The slump flow [1] with J-ring is a variation of the normal slump flow for which a J-ring is put around the cone before lifting it. T_{50} is the time measured in [s] to reach the 500 mm ring. The blocking step is determined by measuring the height difference between the top of the ring and the middle of the concrete surface within the ring (Δh_0). In addition the height difference between the top of the ring and the surface of the concrete outside the ring within two perpendicular directions are measured (Δh_{y1}, Δh_{y2}, Δh_{x1}, Δh_{x2}). The blocking step B_J in [mm] is calculated as follows:

$$B_J = \frac{(\Delta h_{x1} + \Delta h_{x2} + \Delta h_{y1} + \Delta h_{y2})}{4} - \Delta h_0$$

2.4.3 Visual Segregation Index (VSI)

VSI [2] was measured on fresh concrete within the mixer (VSI^m) and on the flow board (VSI^b) after determination of slump flow.
Table 2 shows the VSI rating within the mixer.
Table shows correspondingly the VSI rating on the flow board. A castable concrete should have a VSI^m between 0 and 0.5 and a VSI^f between 0 and 0.6.

Table 2: VSI^m measured directly after the end of mixing in the concrete mixer

0 / 0.1	Stable and homogenous concrete
0.2 / 0.3	Creamy surface and formation of small air bubbles, but still stable.
0.4 / 0.5	Incipient separation, lots of small air bubbles/pores, tendency of sludge layer, formation of black film on the surface.
0.6 / 0.7	Clear signs of separation, strong ”boiling”, sludge layer, black film, coarse aggregates sinking towards the bottom of the mixer.
0.8 / 0.9	Strong boiling, clear water layer, 5-20 mm sludge layer, aggregates lying at the bottom of the mixer.
1	Complete separation.

Table 3: VSI^f measured on concrete on the flow table directly after a slump flow measurement

0 / 0.1	Stable and homogenous concrete. Aggregates and paste flow towards the rim of the sample.
0.2 / 0.3	Stable and homogeneous concrete that flows well, but has become a shiny surface with possible black spots (usually unburned coal residue liberated from the fly ash when the hollow spheres are crushed upon grinding).

0.4 / 0.5	Has additionally a hint of a paste rim at the outer edge of the spread, but the aggregates follow the flow towards the edge. Still stable.
0.6 / 0.7	Clear rim of paste at the outer edge of the spread. Coarse aggregates tend not to flow towards the edge of the spread (are left in the middle of the spread).
0.8 / 0.9	Additional separation of water/paste at the outer rim of the spread.
1	Complete separation

2.4.4 Rheological Segregation Index (RSI)

The RSI [3] is determined using a 4SCC rheometer produced by ConTec with a special rotor which simulates a dynamic separation process by pushing the coarser aggregates aside. After 60 s the rheological parameters G and H of the resulting separated slurry are measured. G relates to the yield stress and H to the viscosity.

RSI value is calculated as follows:

$$RSI = \frac{\alpha}{\sqrt{H \cdot f_{av} + G}} - \beta \qquad with\ \ \alpha = 12\ and\ \beta = 0.25$$

The RSI value has been calibrated to the VSI^{m} and has hence the same limits for stability.

2.4.5 Sieve segregation index (SSI)

For the SSI [4] about 10 litres of concrete is filled into a container. The container is put on a height, covered and left standing without being shaken for 15 minutes. A sieve and a receiver are put on the balance. The weight of the receiver alone is m_p. After the required time is elapsed, about 5 kg, m_c, of concrete from the container is poured upon the sieve (5 mm). The exact mass of the concrete poured onto the sieve is recorded, m_c. The concrete is left for about 2 minutes on the sieve, after which the mass of the concrete passed through the sieve is determined (m_{ps}). The sieve segregation index is than:

$SSI = ((m_{ps}-m_p)\times 100\%)/m_c$

For

0<SSI<15	the SCC has a satisfactory segregation resistant;
15<SSI<30	the segregation resistance is questionable;
30<SSI	the segregation resistance is inadequate and the SCC is ranged unstable

2.4.6 Visual segregation on cut surfaces of hardened concrete

The method is based on a test developed by Müller [5]. Two 150/300 mm steel cylinder moulds were filled with concrete; one cylinder was given 10 hits on a fall table to simulate the dynamic impact in situ, and the other one not. The cylinders were cast 30 – 40 minutes after water addition. After some time of curing the cylinders were cut along their axes parallel to the casting direction. The segregation was then evaluated from the thickness in mm of the matrix layer on the top; "matrix separation", and from the distance in mm from the top down to the coarse aggregates; "aggregate segregation".

2.5 Mixing and testing procedures of the matrices

2.5.1 Overview

Equivalent matrices were prepared for all concretes given in Table 1 except for the “extra” concretes. Note that there are 9 matrices while 8 concretes. The ninth, "wc0.61wp0.43sp1.22", was made to see the influence of reducing the SP content without changing other parameters. The sand fines were sieved from the 0-2 mm crushed sand and the same cement, STD-FA, and SP, Dynamon SX-N, were used as for the concrete. . The particle size distributions of the sand fines and the cement determined by laser diffraction are shown in Fig 3. The mix proportions are given shown in Table 4.

Table 4. Mix proportions of the matrices.

No.	w/c	w/p	add. f/c (mass based)	V_f/V_p (volume based)	SP dosage (liq. Per cem.)	matrix code
1	0.61	0.47	0.298	0.240	1.22	wc0.61wp0.47p1.22
2	0.61	0.43	0.417	0.307	1.22	wc0.61wp0.43p1.22
3	0.61	0.43	0.417	0.307	1.37	wc0.61wp0.43p1.37
4	0.56	0.46	0.218	0.188	1.55	wc0.56wp0.46p1.55
5	0.56	0.43	0.301	0.242	1.74	wc0.56wp0.43p1.74
6	0.56	0.39	0.435	0.316	2.50	wc0.56wp0.39p2.50
7	0.51	0.43	0.186	0.165	2.13	wc0.51wp0.43p2.13
8	0.51	0.39	0.307	0.246	2.80	wc0.51wp0.39p2.80
9	0.51	0.35	0.456	0.326	3.93	wc0.51wp0.35p3.93

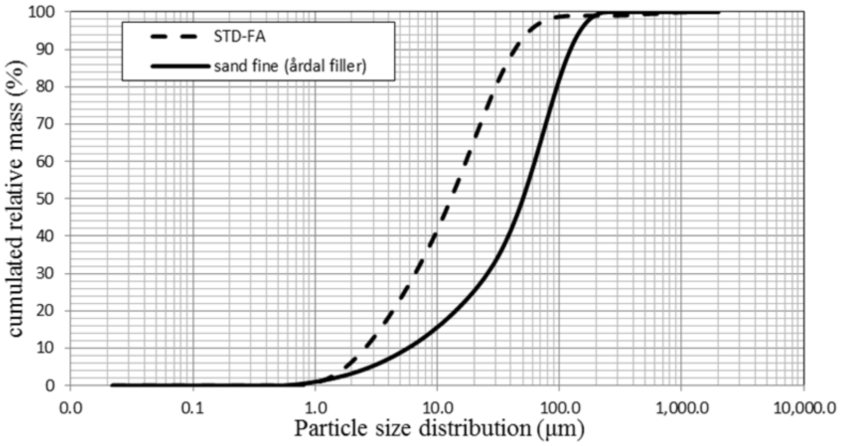


Fig. 3: Particle size distribution of cement (STD-FA) and sand fines

2.5.2 Mixing and testing procedure

For each mix, 3 l of matrix was prepared using a Hobart mixer according to the following procedure: 1 min dry mixing of cement and filler at low speed, then water and superplastisizer is added while mixing for 2 min at lower speed (591 rpm beater speed), followed by 1 min mixing at middle speed (1485 rpm beater speed). Then the matrix is left to rest for 5 min during which the bottom of the container is checked and mixed by hand (using gloves) to break up possible agglomeration of cement. Finally the matrix is mixed for 1 more minute at middle speed (1485 rpm). All experiments start at around 10 min after water addition.

Four tests were performed on the matrices:

- Hydrostatic pressure test (HYSPT) on sedimentation,
- Total bleeding,
- Mini slump flow test,
- Flow resistance (FlowCyl)

The three first tests were performed in parallel on the same batch, while FlowCyl was performed on a separate batch.

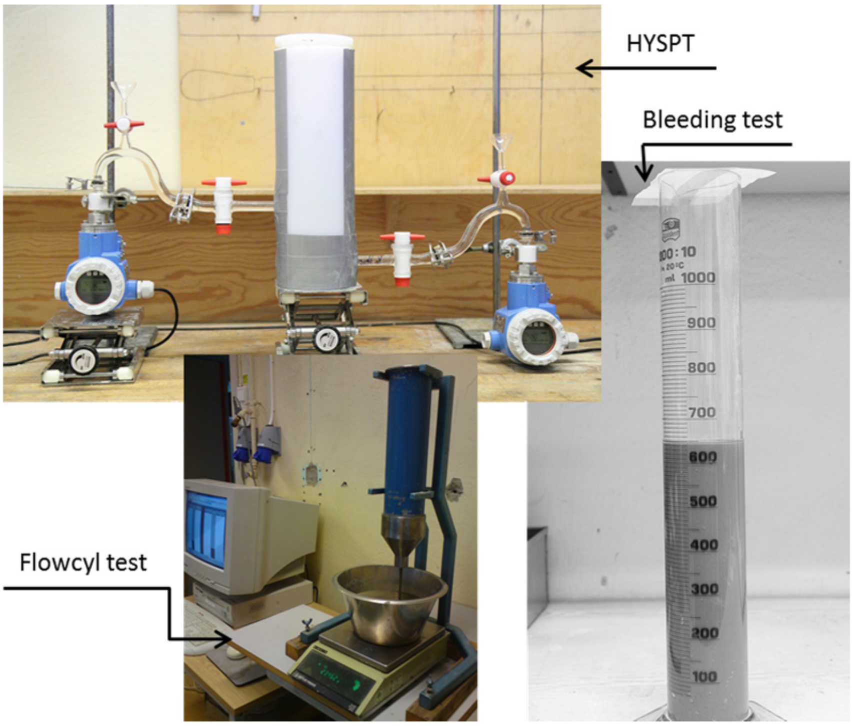


Fig. 4: Test set up for HYSPT, bleeding and FlowCyl

2.5.3 Hydrostatic pressure test (HYSPT) and bleeding

The application of the HYSPT to test the sedimentation behaviour of paste relies on the restricted Stokesian settlement of particles causing changes in the solid fraction, Φ, and thus changes in the fresh density, ρ, at a given height, h, and time, t. In the homogeneous settling zone the hydrostatic pressure, p, reduces according to

$$p(t,h) = \rho gh = [(\rho_l\ (1-\Phi(t,h))+ \rho_s\ \Phi(t,h)]gh$$

Here ρ_l is the liquid density and ρ_s is the solid particle density. By accurately measuring pressure p at depth h and time t, both solid fraction and state of flocculation can be assessed from the pressure drop vs. time curves (dp/dt). The method is discussed more in detail in [6].

The HYPST uses an opaque container with an inner diameter of 100 mm (Fig 4). Bleeding was measured in a 1 l transparent graduated glass with an inner diameter of 65 mm (Fig 4). The filling height of the matrix samples was 200 mm both for the HYSPT and the bleeding test. According to the Richardson-Zaki theory, the wall effect on bleeding is very small for containers with this size, hence the bleeding water depth should be the same for the HYPST and bleeding test samples. The HYSPT and total amount of bleeding was measured approximately 4 hours after water addition. Within the whole period, the containers were sealed limit evaporation.

2.5.4 Flow resistance and minislump

The FlowCyl tests performed according to Mørtsell [7] were carried out approximately 15 min after water addition. The main cylinder diameter is 80 mm, the outlet diameter is 8 mm, the filling height from the sample surface to the bottom outlet is 390 mm and the distance from the outlet to the balance is 150 mm. See also Fig. 5.

Based on the densities of the matrices shown in the Table 1 and FlowCyl setup information, the flow resistance number, λ_Q, defined as the ratio of the area under the flow curve of the tested sample to that of the ideal fluid, can be calculated. Hence, λ_Q is always between 1 (low flow) and 0 (high flow). λ_Q relates to the plastic viscosity [7].

The cylinder used for the matrix mini slump flow tests is 35 mm in height and 24 mm in diameter.

3 Results

3.1 Matrices

3.1.1 Consistency; flow resistance and minislump

The results, given in Table 5, confirm the known effect of changing filler and SP content: The flow resistance, λ_Q, increases when adding filler (reduced w/p); compare No.2 and No.1 having the same SP content, and when reducing the SP content; compare No.3 and No.2 having the same w/p. In all other cases both w/p and SP varied at the same time. Then, λ_Q still increases with decreasing w/p, but increases apparently also with increasing SP amount, see Fig 5. This tells us that w/p is more dominant than SP content with respect to the λ_Q. Note however that it is questionable whether the SP is as effective at these dosages which are a lot higher than applied in practice.

The results also show that the SP amount for matrices having the same w/p always increases with decreasing w/c (No.1 > No.4, No.3 > No.5 > No.7 and No.6 > No.8), and that λ_Q increases correspondingly. This supports the hypotheses that cement influences SP-demand more than sand fines, as stated in section 2.1.

Table 5. Flow resistance ratio λ_Q and yield stress calculated from the mini-slump flow

No.	matrix code	density (kg/m^3)	slump flow d (cm)	yield stress (Pa)	flow resistance λ_Q
1	wc0.61wp0.47p1.22	1805	9.9	2.7	0.38
2	wc0.61wp0.43p1.22	1844	9.3	3.7	0.61
3	wc0.61wp0.43p1.37	1844	9.9	2.7	0.54
4	wc0.56wp0.46p1.55	1818	9.0	4.3	0.56
5	wc0.56wp0.43p1.74	1846	9.2	3.9	0.55
6	wc0.56wp0.39p2.50	1888	9.7	3.1	0.62
7	wc0.51wp0.43p2.13	1850	9.0	4.4	0.60
8	wc0.51wp0.39p2.80	1892	9.2	4.0	0.66
9	wc0.51wp0.35p3.93	1938	9.1	4.4	0.73

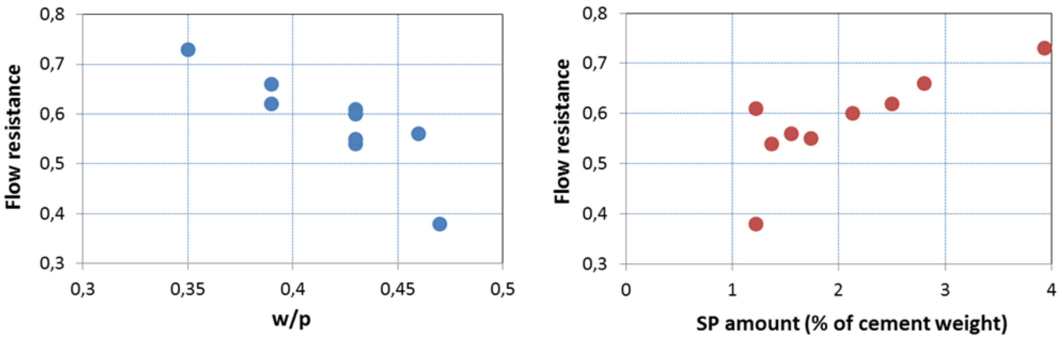


Fig. 5: Flow resistance (from FlowCyl) versus w/p and SP content

3.1.2 Stability; bleeding and sedimentation (HYSPT)

For the same series of matrices, the total bleeding was measured and Fig. 7 shows the total bleeding of all matrices at 4 hours after mixing. It is interesting to see that:

By comparing matrix No. 1-3, the filler addition helps to decrease the total bleeding and the higher dosage of SP leads to more bleeding. There is a diluted grout layer between the clear bleeding water and sediment matrix body, possibly because the sedimentation process did not finish at that time for the matrix with relatively high dosage of SP (matrix No. 3). From HYSPT it was observed that adding more filler accelerates the sedimentation rate, but at the same time it leads to less bleeding; more SP stabilizes the matrix because it lowers the sedimentation rate, but it could possibly cause more bleeding. These two phenomena show that total bleeding amount might not reflect the stabilization effect well for cement matrices because it does not indicate the homogeneity of the whole suspension. As suggested by the conceptual model for sedimentation and bleeding shown in [6], the sedimentation of matrix is a process which results in the formation of different zones during different stages of the sedimentation process. Hence, in addition to the total amount of bleeding, the inhomogeneity of the matrix body is affected by the particle flocculation, cement hydration and structural buildup.

For the other matrices, No. 4-9, it is interesting to see that even with higher SP dosages, there is no bleeding after 4 hours but a “setting” like (thixotropic) behavior was observed, as Fig. 5 shows, which is a common observation for low w/p matrices, and the time for this phenomena happened varied from half to 1.5 hours which depends on the superplasticizer dosage. After a slight shake for the container, the matrix can flow smoothly.

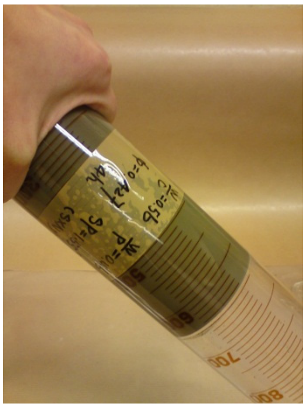
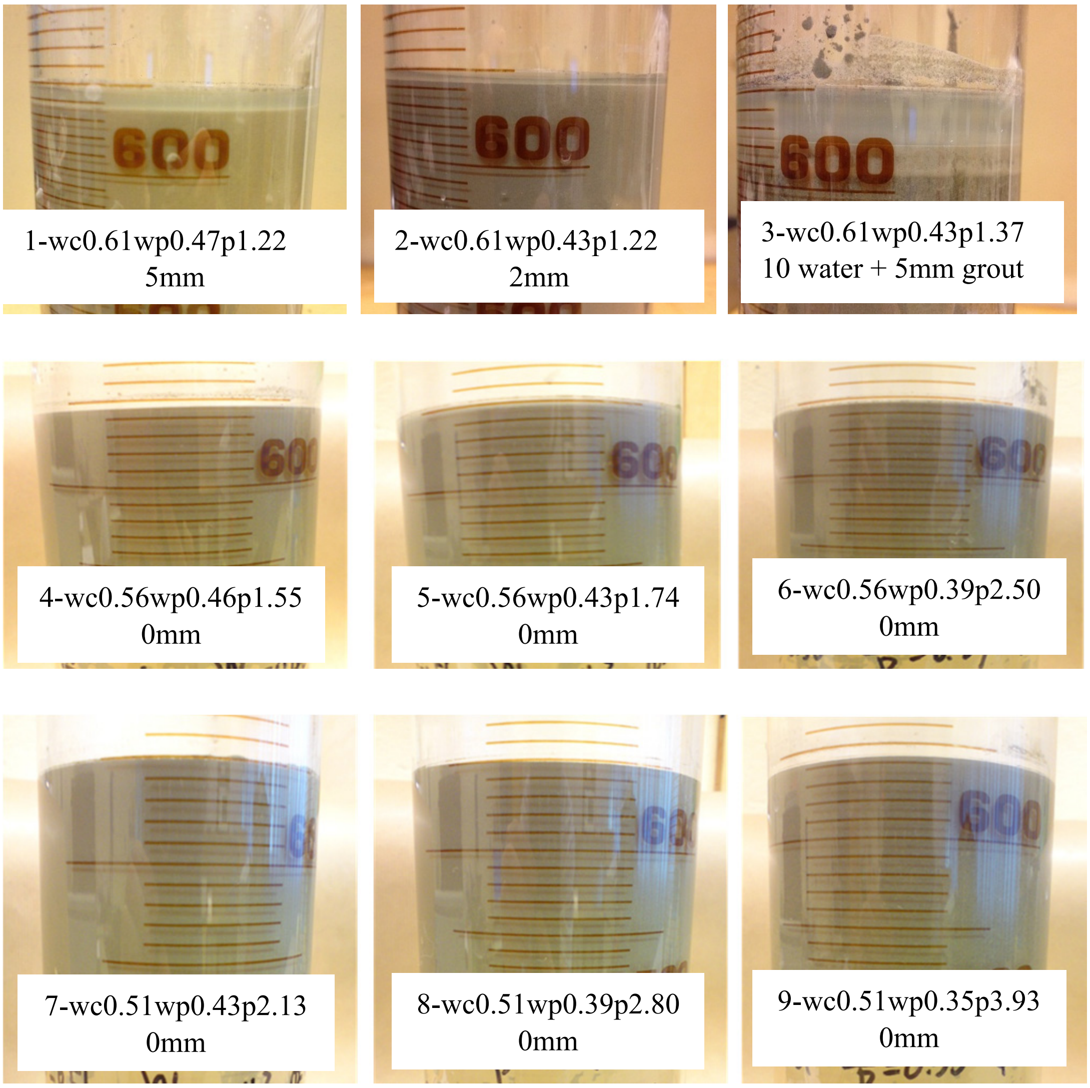


Fig. 6: “Thixotropic like” behavior of low w/p matrices (the picture was taken at 2 hours after mixing for matrix 4- wc0.56wp0.46p1.55



1-wc0.61wp0.47p1.22
5mm

2-wc0.61wp0.43p1.22
2mm

3-wc0.61wp0.43p1.37
10 water + 5mm grout

4-wc0.56wp0.46p1.55
0mm

5-wc0.56wp0.43p1.74
0mm

6-wc0.56wp0.39p2.50
0mm

7-wc0.51wp0.43p2.13
0mm

8-wc0.51wp0.39p2.80
0mm

9-wc0.51wp0.35p3.93
0mm

Fig. 7: Total bleeding of the matrices (4 hours after mixing)

To study the homogeneity and sedimentation process of the matrices before setting, the Hydrostatic Pressure Tests (HYSPT) were carried out. Fig. 8 shows the pressure change in the whole sedimentation process mainly due to particle moving within 1-3 hours and further reaching the plateau until 4 h. It is clear that the matrices can be classified into two groups by different sedimentation performances. The matrices with higher w/c and proper superplasticizer dosage show pressure curves that are typical for pressure change caused by the particle movement. However, the sedimentation process of other matrices showing strong thixtropic properties was highly influenced by the structural buildup of the matrices. Lower w/c and/or higher superplasticizer dosage caused stronger structural buildup and thus faster pressure drop. It is coincide with the bleeding detection as shown above, both measurements confirm the thixtropy of the matrices.

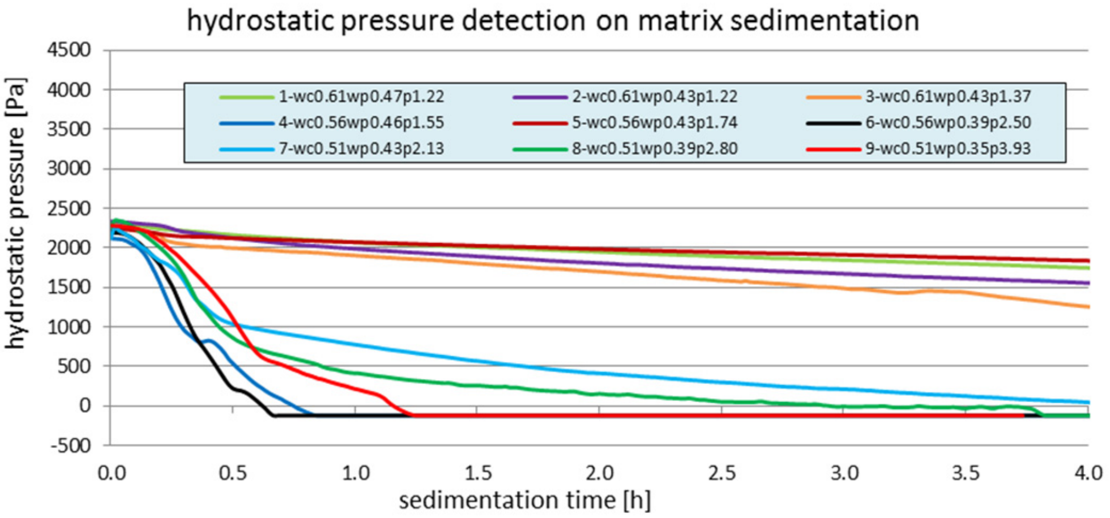


Fig. 8: the pressure detection results by HYSPT on sedimentation for all matrices

3.2 Concrete tests, overview of slump flow variation, flow rate (t_{500}) and Blocking resistance (Bj)

Each concrete was performed only once, i.e. the reliability regarding batch to batch variation is not known for the present investigation. However, a previous study of the repeatability on quite similar concretes using the same methods and laboratory, show very low scatter [8]. Also, reasonable reliability is indicated as the flow rate and blocking resistance results are rather consistent and the influence of the material factors varied on these parameters was according to previous experience [8].

The target slump flow was 675 mm. The actual values varied within the acceptable limits; between 645 and 700 mm, except for the "Minus -15" concrete which got 610 mm. An overview of all results is given in Table 6.

Table 6. Overview of results. 10 and 60 refers to minutes after water addition. SU and segregation are given in mm, and t_{500} in seconds

Concrete		SU		t500		SUR		Bj		VSI 10		VSI 60		RSI		SSI		Pasteseg		Aggr. Seg	
		10	60	10	60	10	60	10	60	Mixer	Board	Mixer	Board	10	60	10	60	no hit	hit	No hit	hit
Minus	-15	610	600	3,1	2,7	450	495	63	51	0,85	0,80	0,65	0,65	0,4	0,4	9	8	0	2	0	2
	0	670	620	1,2	1,7	605	495	37	52	0,95	0,90	0,75	0,75	0	0,1	27	19	2	4	2	6
Ref	-15	660	625	2,7	4,0	505	475	47	53	0,95	0,90	0,85	0,65	0,8	0,5	17	10	3	5	4	7
	0	675	645	1,5	2,7	545	575	42	36	0,75	0,55	0,65	0,45	0,2	0,6	34	13	0	3	0	10
	+15	685	660	1,1	1,4	620	610	39	32	0,75	0,55	0,55	0,45	0,4	0,7	33	13	0	3	0	10
Plus	-15	645	620	4,6	6,1	535	595	43	36	0,80	0,75	0,75	0,75	0,4	0,3	17	12	2	2	0	0
	0	675	655	1,9	2,4	600	635	35	28	0,80	0,55	0,75	0,60	0,9	0,8	31	20	4	5	5	7
	+15	690	690	1,1	1,6	645	610	24	30	0,70	0,55	0,55	0,45	0,9	0,7	25	14	0	0	4	10
Extra	-15	680	685	2,5	5,4	570	605	36	33	0,40	0,35	0,30	0,10	0,2	0,2	4	8	0	1	0	5
	0	700	687	1,5	1,9	na	665	30	27	0,65	0,50	0,55	0,40	0,8	0,6	17	21	1	4	7	8
	+15	690	675	1,0	1,2	683	635	18	25	0,70	0,40	0,55	0,35	0,8	0,7	18	12	1	1	2	10

Note that the actual matrix content differs from the nominal one because the amount of SP used was different from the amount used in the proportioning of the concretes. This means that the -15 concretes contain 2-7 litres more matrix than the nominal values, while the +15 matrices are quite similar to the nominal ones. The results are presented in relation to the nominal values.

The flow rate, expressed by t_{500}, decreases with increasing water content, as expected, see Fig 9. The influence of sand content is not that consistent. This may be the result of two opposing effects when increasing the fine sand content; one being the increased matrix content itself (giving decreased t_{500}), the opposing one being decreased w/p (giving increased matrix viscosity, implying increased t_{500}). And there is a tendency, although not consistent, that the concretes with the highest t_{500} are the ones with matrices with high flow resistance (implying high viscosity), see Table 5. Furthermore, for high w/p ("0" and "+15" concretes) t_{500} seems to be less influenced by the matrix content. For lower w/p ("-15" concretes), resulting in a more viscous matrix, the t_{500} tends to increase with increasing matrix volume with fines. This latter observation is quite clear in the 60 minutes measurements, i.e. when the matrices are even more viscous as compared to the 10 minutes measurements. As the difference between the “-15” and “0” mixes is larger than the difference between the “minus”, “ref” and “plus” series (the different dotted lines), the decreasing w/p seems to more important than increasing matrix content for the low w/p mixes.

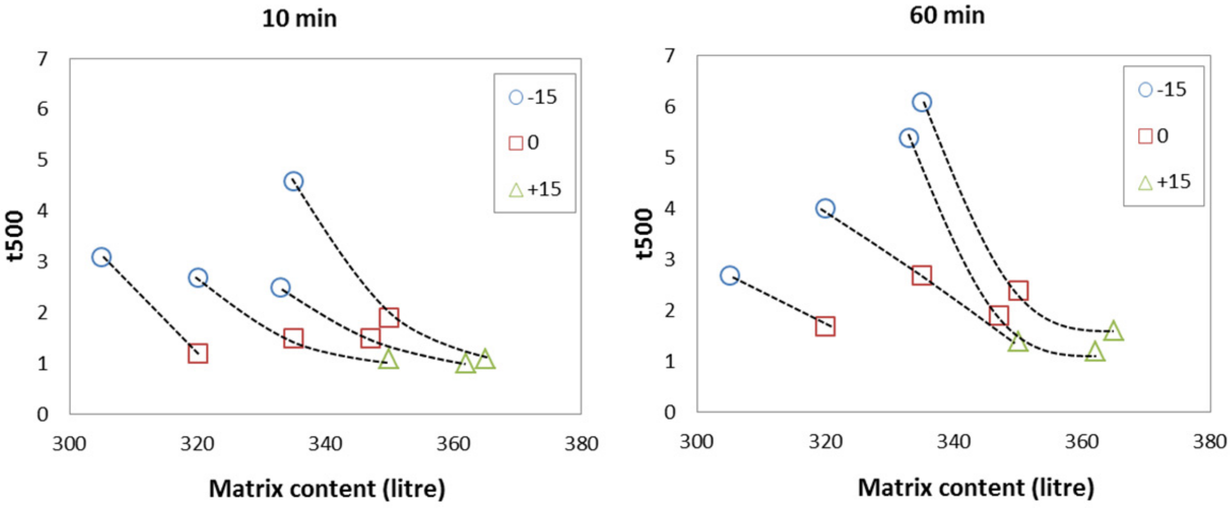


Fig 9: t_{500} versus matrix content measured 10 and 60 minutes after water addition, respectively. Each label type represents concretes with the same water content, see Table 6. Each dotted line represents concretes with the same sand composition series; from left: "minus", "ref", "extra" and "plus" given in Table 6.

The blocking resistance decreased with increasing matrix content, as expected, see Fig 10. As can be seen also, the results did not reveal any significant differences to whether the matrix content is increased by water or sand fines.

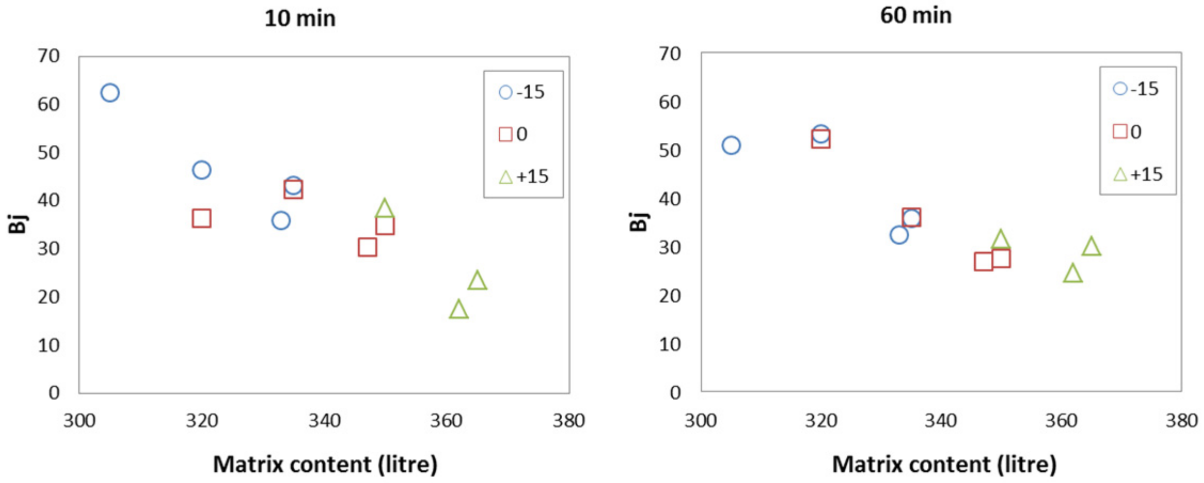


Fig 10: Blocking resistance, B_j, versus matrix content measured 10 and 60 minutes after water addition, respectively. Each label type represents concretes with the same water content, see Table 6.

3.3 Correlation between results from the stability tests methods

It is a common opinion, at least from a practical point of view, that a visual observation is the most reliable way to evaluate stability. This was also confirmed in a previous COIN investigation on the comparison of the present test methods [8]. Therefore, the correlation is done against the VSI. Furthermore, the mentioned investigation confirmed that the VSI from the mixer (VSI^m) is more reliable than the one on the board (VSI^b). Hence, VSI^m is used. The present investigation confirms the previous investigation in that VSI^b is generally lower than VSI^m, as shown in Fig 11.

It is usual to distinguish between static and dynamic segregation. The present test methods reflect both to different degrees; VSI and RSI are mostly dynamic, and SSI and VSHC are mostly static. This may be an important reason for the bad correlation between the methods as shown below, especially knowing that the matrix investigations showed strong thixotropic behaviour for some of the matrices (thixotropy influences static stability rather than dynamic stability).

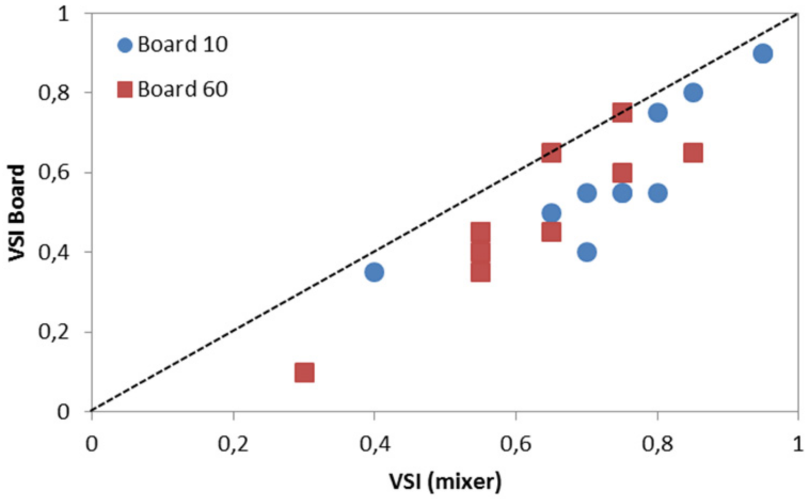


Fig. 11: Correlation between Visual Segregation Index determined from the slump flow board and mixer, respectively. Measurement on all concretes, 10 and 60 minutes after water addition, respectively.

Previous investigations showed that the **Reological Segregation Index** test does not give reliable results when used on concretes with low stability [3]. This is confirmed by the present tests in that the correlation with VSI^m is rather poor for VSI^m values higher than approximately 0.7 (Fig. 12).

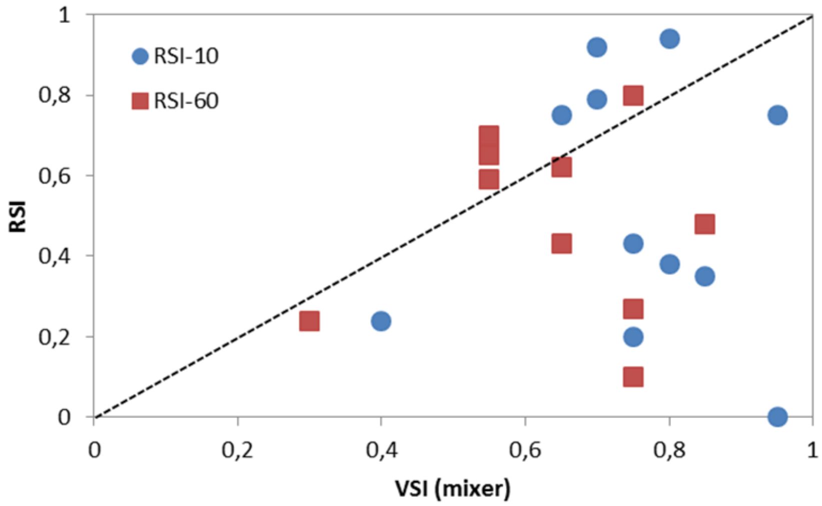


Fig. 12: Correlation between Reological Segregation Index and Visual Segregation Index (mixer), respectively. Measurement on all concretes, 10 and 60 minutes after water addition, respectively.

The **Sieve Segregation Index** did not show a good correlation to the VSI^m, see Fig 13. This is also in agreement with the previous investigation mentioned. Since SSI reflects more static stability and VSI more dynamic stability, it is interesting to note that the highest SSI-values (above approx. 25 at 10 minutes after water addition) represent concretes with the highest w/p and simultaneously matrices with no or low thixotropy, and the lowest SSI value (9 at 10 min) represent one of concretes with the lowest w/p and simultaneously high thixotropy. Also, the two data points to the very right (both with VSI of 0.95 ≈ "complete separation") represent one concrete with high w/p and simultaneously low thixotropic matrix, and the lowest one concrete with the lowest w/p and simultaneously high thixotropic matrix. This supports hypothesis that thixotropy influences both static (SSI) and dynamic (VSI^m) methods in different ways and thereby leads to a bad correlation between these test methods.

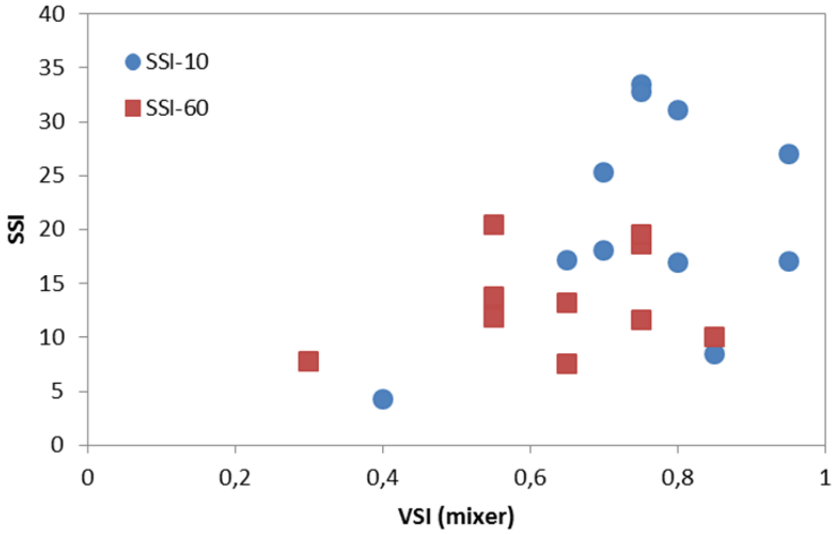


Fig. 13: Correlation between Sieve Segregation Index (SSI) and Visual Segregation Index (VSI^m). Measurement on all concretes, 10 and 60 minutes after water addition, respectively.

As can be seen from Fig.'s 11-13, only a few concretes have acceptable stability according to the test methods. The **Visual Segregation on Cut Surfaces of Hardened Concrete** (VSHC), however, did not give the same impression as both matrix and coarse aggregate segregation seemed rather low for most concretes, see pictures in APPENDIX B. Hence, the correlation with VSI^m is poor, as can be seen in Fig 13 (60 min results, only, since the cylinders were cast 30-40 minutes after water addition). Then, given that the VSHC is close to reality, since it visualises the result in hardened concrete, it seems that VSI underestimates the stability (at least considering static stability).

Nevertheless, there is a trend that the matrix segregation increases with increasing VSI^m (Fig 14 left), while no such trend can be seen concerning coarse aggregate segregation. This suggests that VSI^m predicts matrix segregation rather than coarse aggregate segregation.

The correlation between VSHC and SSI is also weak, but it seems that coarse aggregate segregation correlates better than matrix segregation (see Table 6).

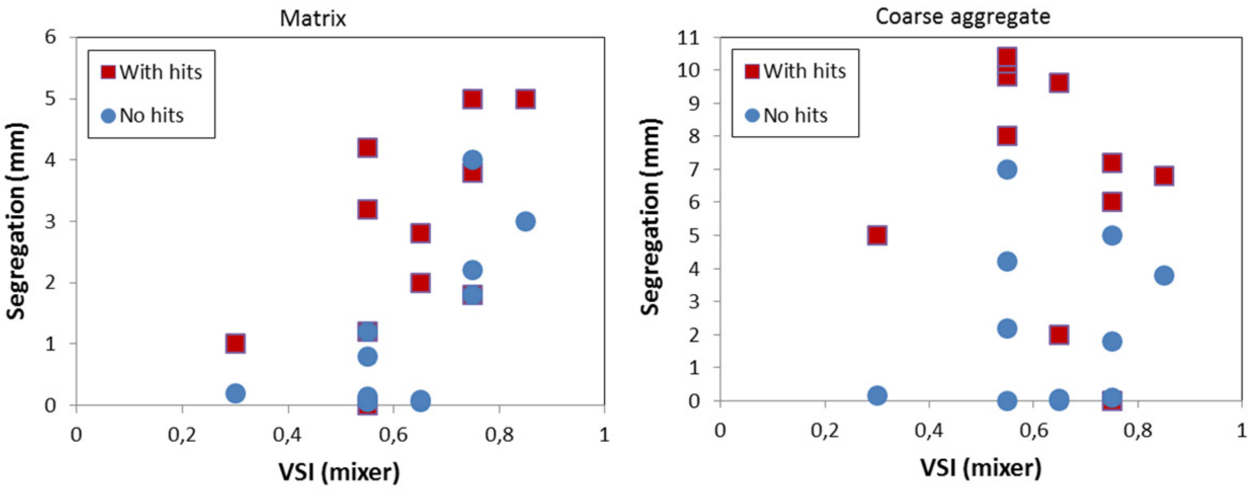


Fig. 14: Correlation between Visual Segregation on Cut Surfaces of hardened concrete and Visual Segregation Index (mixer). Measurement on all concretes, 60 minutes after water addition.

3.4 Influence of matrix content

3.4.1 Visual Segregation Index, VSI^m

According to the VSI^m test, all concretes, except the ones with finer sand, appeared to be quite unstable, see Fig 15. The VSI^m-results can be put in three groups: Group 1 is the "minus-concretes" (low in sand), seen as the left trend line in Fig 15, group 2 is the "ref"- and "plus"-concretes, and group 3 is the "extra"-concretes (with another sand type), seen as the lower trend line in Fig 14. The trends are similar for the 10 minutes and 60 minutes measurements, and all concretes are more stable at 60 minutes, as expected.

The group 2 results, showing a VSI^m increase with decreasing water content, are somewhat surprising since a decrease of water content, resulting in lower w/p and less matrix, was expected to give better stability (decreased VSI^m). The matrix tests referred in section 3.1.1 (Table 5) support the expectations as they show increasing flow resistance with decreasing w/p (decreasing water content), even when the SP dosage was considerably increased to retain flowability, and the minislump tests on the matrices confirmed fairly constant dynamic yield stress values (Table 6). We have not found any plausible explanation for this contradiction, other than that the method itself is maybe not sufficiently reliable for rather unstable SCC, i.e. it underestimates the stability (see also the VSHC discussion later). For example, the apparent "strong boiling" seen may be given too much attention. This is supported by that the concretes with the finer sand ("extra") giving better stability, showed expected influence of changed water content.

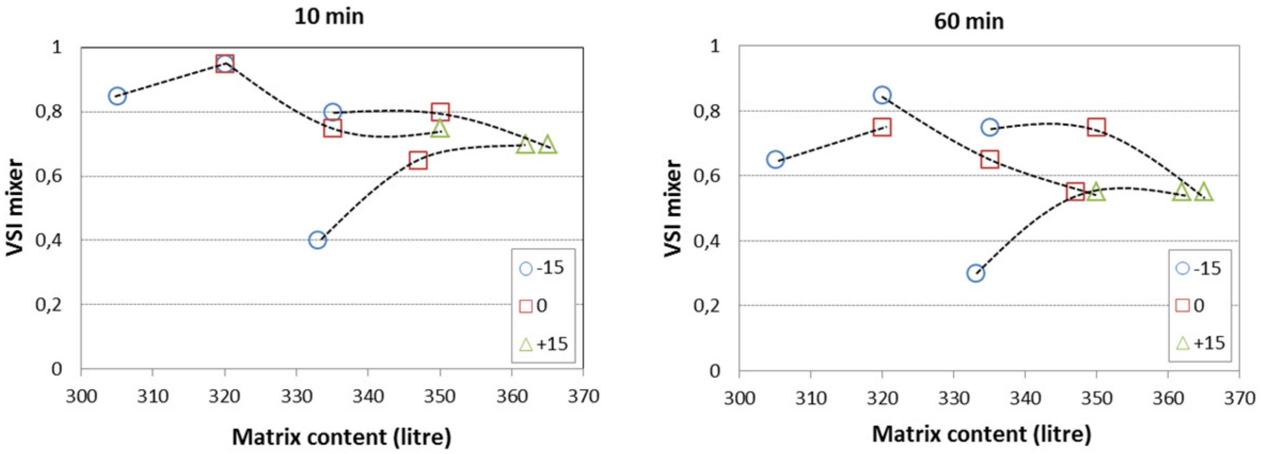


Fig. 15: Visual Segregation Index versus matrix content measured 10 and 60 minutes after water addition, respectively. Each label type represents concretes with the same water content, see Table 6. Each dotted line represents concretes with the same sand composition, as given in Table 1.

3.4.2 Sieve Segregation Index, SSI

The results are quite consistent in that -15 litres of water (from the "0-concretes") always improved the stability as expected (reduced w/p and matrix content), see Fig 16. In this case the thixotropy of the low w/p matrices (see section 3.1.1) probably enhances this effect. The results are also quite consistent in that +15 litres also improved the stability, but which is unexpected. Bleeding may play a role in this: The +15 matrices showed bleeding (see section 3.1.2) which may contribute to improved stability of the "drained" matrix. This is supported by the fact that the matrix of the concrete richest in sand (the right curve in Fig 16) showed the most bleeding and at the same time the largest stability improvement. Bleeding of the concretes was not measured, so this hypotheses can not be verified.

In general, the results indicate that changing the water content influences the stability more than changing the sand content, and the influence of sand content is not consistent.

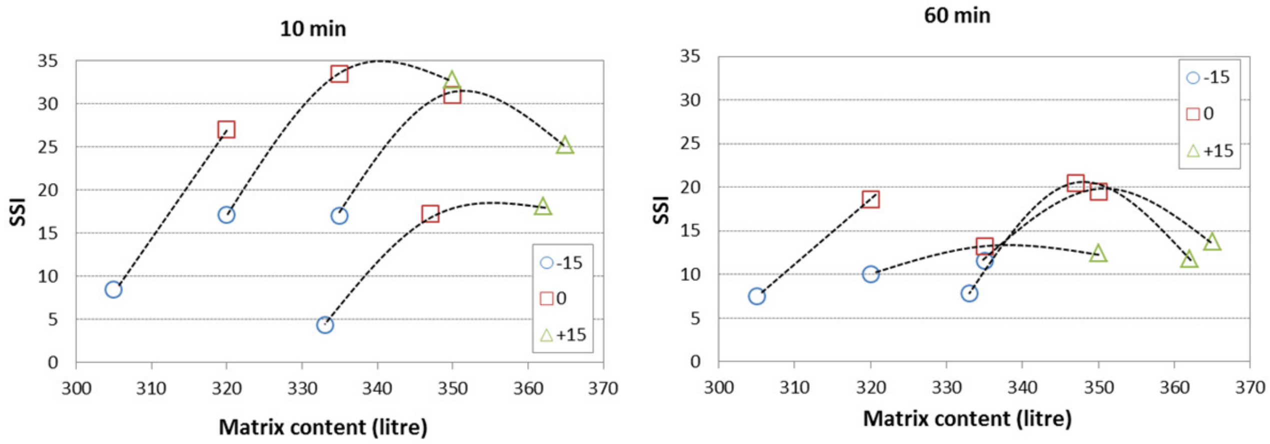


Fig. 16: Sieve Segregation Index versus matrix content measured 10 and 60 minutes after water addition, respectively. Each label type represents concretes with the same water content, see Table 6. Each dotted line represents concretes with the same sand composition, as given in Table 1.

3.4.3 Visual segregation on cut surfaces of hardened concrete, VSHC

The test was supposed to represent the substantiation of stability. The pictures taken of the cut surfaces (APPENDIX B) reveal two types of segregation; matrix and coarse aggregate (approx. 4 mm). The **matrix segregation** in mm as shown in Fig 17, is apparently rather inconsistent with respect to changes of water and sand content. Note that we do not have any experience with the test method, which means that we do not know how representative one cylinder is considering any variation in the making procedure. Müller [6] concluded that the geometry is sufficient to give reliable assessment of stability.

It is however rather clear that the hit caused more segregation. Note also that the high w/p concretes (triangles) appeared relatively stable. This was unexpected, but is in line with the SSI-results, and could thus be the effect of bleeding as discussed in the previous section.

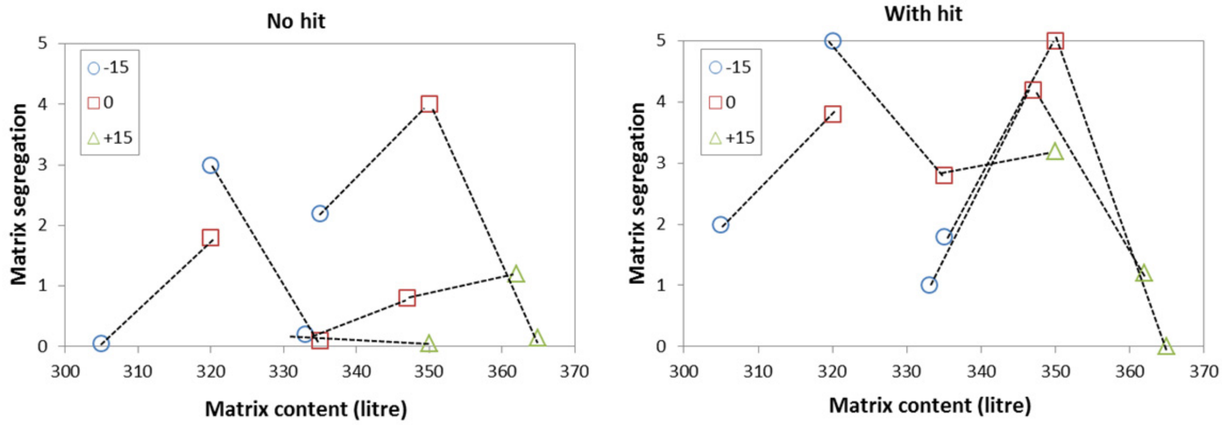


Fig. 17: Visual Matrix Segregation of Hardened Concrete with and without hit versus matrix content. Each label type represents concretes with the same water content, see Table 6. Each dotted line represents concretes with the same sand composition, as given in Table 1.

The **coarse aggregate segregation** (Fig 18) seems to fall in the same picture as the matrix segregation, when considering the specimens without hit. With hit, the picture is more in line with the expected; increasing segregation with increasing water content (reduced w/p). The most conspicuous is that the hit action brings the high w/p concretes (triangles) from appearing rather stable to unstable (compared with the other concretes). It indicates that the matrix (or maybe the mortar) does not exhibit sufficient resistance to hold the coarse aggregates in a dynamic situation.

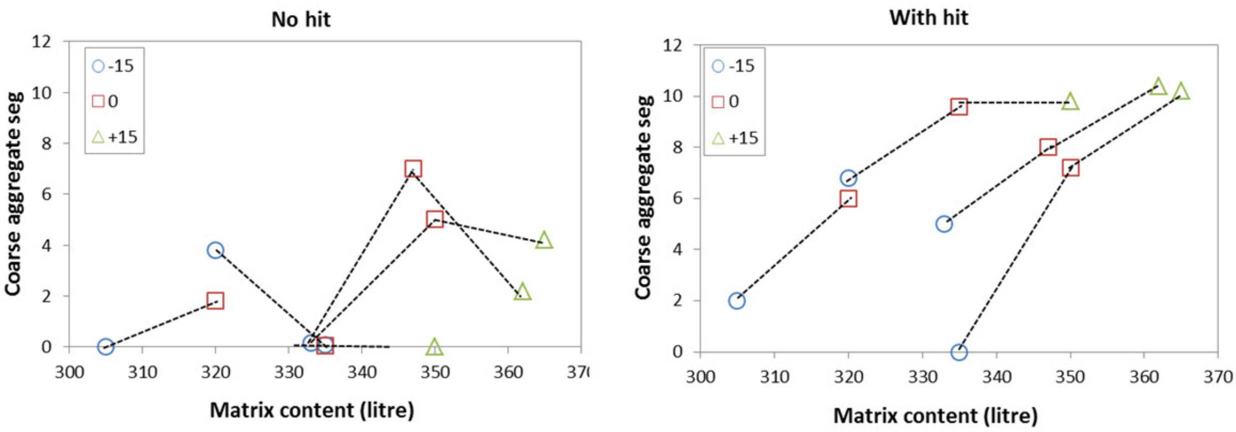


Fig. 18: Visual Aggregate Segregation of Hardened Concrete with and without hit versus matrix content. Each label type represents concretes with the same water content, see Table 3. Each dotted line represents concretes with the same sand composition, as given in Table 1

4 Final assessment - conclusion

Concrete producers experience occasionally unintended variation in the water content as well as the sand particle distribution in daily production of concrete. It results in changed w/c, w/p and matrix content, and they usually adjust the SP-addition to retain the target slump flow. This practical approach was used in the present investigation to consider how such typical variations may influence the stability of SCC.

The current mix design variations indeed influence stability, but it is conspicuous that the influence was not bigger considering a maximum matrix difference of 60 litres in concretes with the same materials. In fact, all concretes appeared to exhibit a rather good static stability. But the main impression of the stability tests is that the results appear rather inconsistent, both considering the relation between different test methods and the influence of the material parameter variation. This is probably influenced by whether, or to which degree, the methods measure static or dynamic stability: For many of the present concretes, the dynamic stability is poor according to the test methods, while the static stability seems quite good for the same concretes. Furthermore, the difference is assumingly influenced by the thixotropic behaviour of several of the concretes (results in improved static stability), and possibly by bleeding (results in increased static stability of the "drained" concrete). It should be mentioned that the superplasticizer content is quite high, and much higher than that recommended in some of the concretes which implies that these concretes would not been used in practice. It is uncertain how the high content influences the results.

The present study is not designed to systematically analyse each of these parameters separately. On the contrary, the change of water and sand content as done here, results in variation of many of the parameters at the same time, and with partly opposing effect on the various stability problems, as elaborated in section 2.2. This leads apparently to an inherent robustness, at least regarding sand grading variation, which is strengthened by thixotropic and bleeding effects.

The question can be raised whether the test methods represent the stability problems in situ, at least the static ones, which normally are of rather strong dynamic character. This will be further investigated in COIN, with the aim to find a method to assess stability of SCC which is reliable and representative for in situ stability problems.

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APPENDIX A

Actual recipes (kg/m^3)

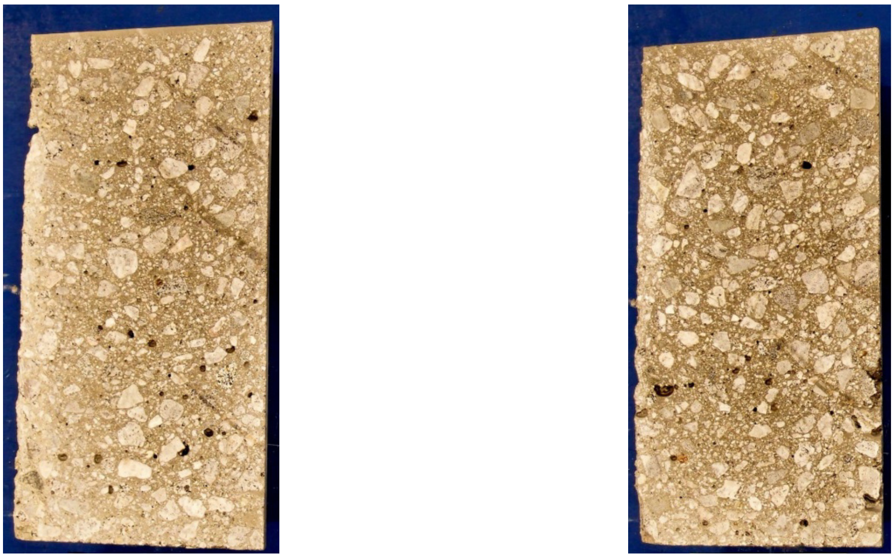
Materials	Minus concrete		Reference concrete			Plus concrete			Extra concrete		
	-15	0	-15	0	+15	-15	0	+15	-15	0	+15
Cement	328	327	327	329	328	328	328	329	330	329	329
Water	170	184	173	186	204	175	187	201	172	186	201
SP	7,2	5,1	9,2	5,7	4,0	12,8	8,2	4,5	8,0	6,1	4,2
Natural sand 0-2	-	-	-	-	-	-	-	-	393	385	376
Crushed sand 0-2	-	-	391	383	374	279	273	267	-	-	-
Natural sand 0-8	1121	1097	727	711	694	838	820	802	729	714	698
Gravel 8-16	747	731	745	730	712	745	729	713	748	733	716

APPENDIX B Pictures of cut hardened cylinders

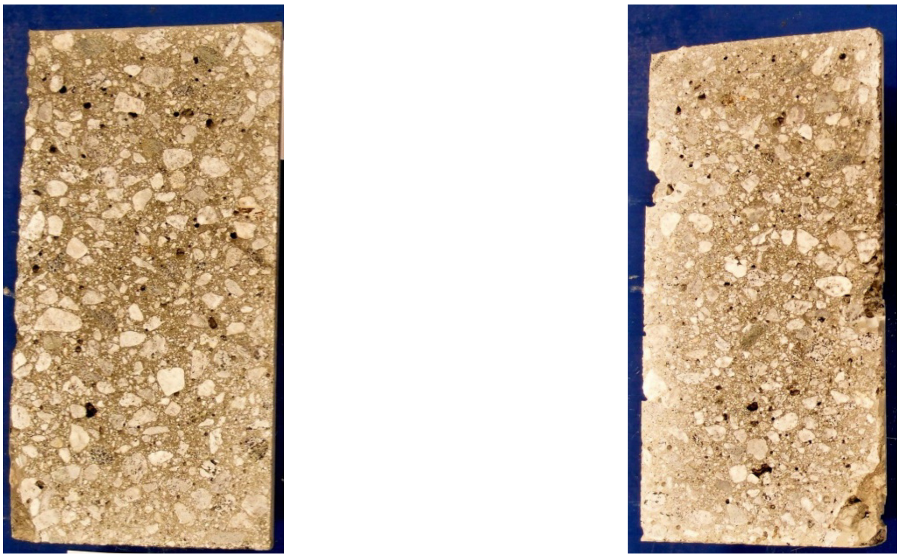
Plus concrete, with and without stroke exposure (left)

Pluss concrete + 15 litre, with and without stroke exposure (left)

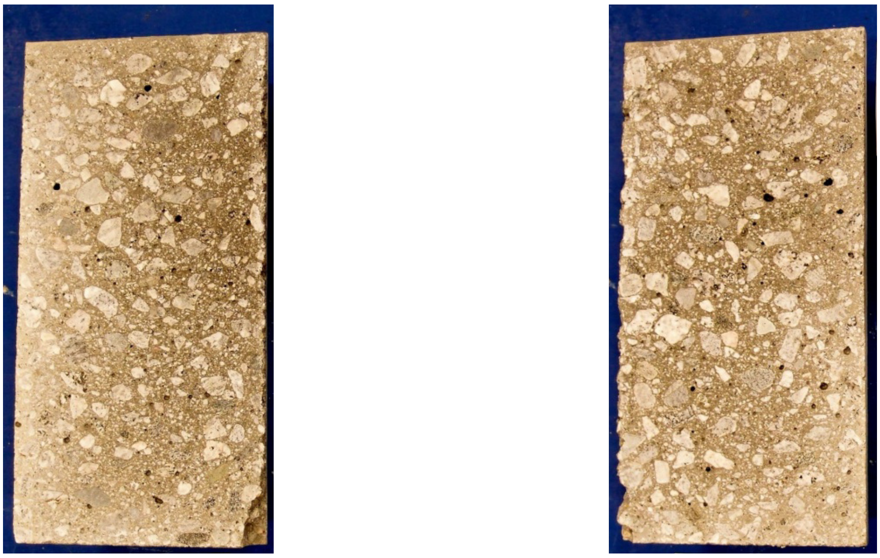
Pluss concrete – 15 litre, with and without stroke exposure (left)



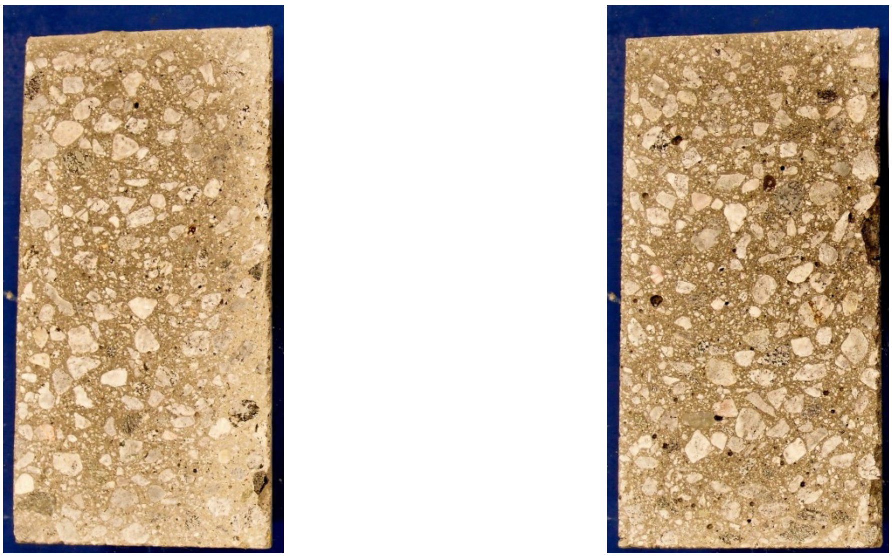
Minus concrete, with and without stroke exposure (left)



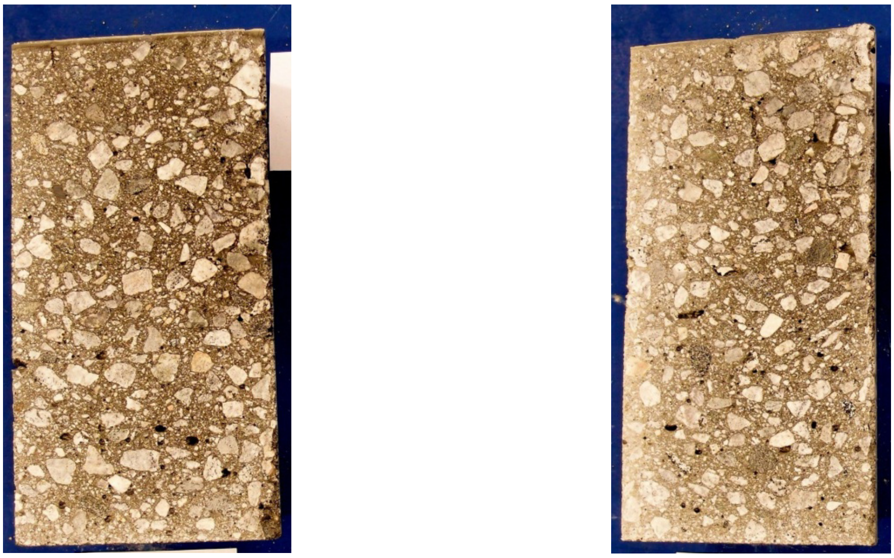
Minus concrete – 15 litre, with and without stroke exposure (left)



Reference concrete, with and without stroke exposure (left)



Reference concrete + 15 litre, with and without stroke exposure (left)



Reference concrete – 15 litre, with and without stroke exposure (left)

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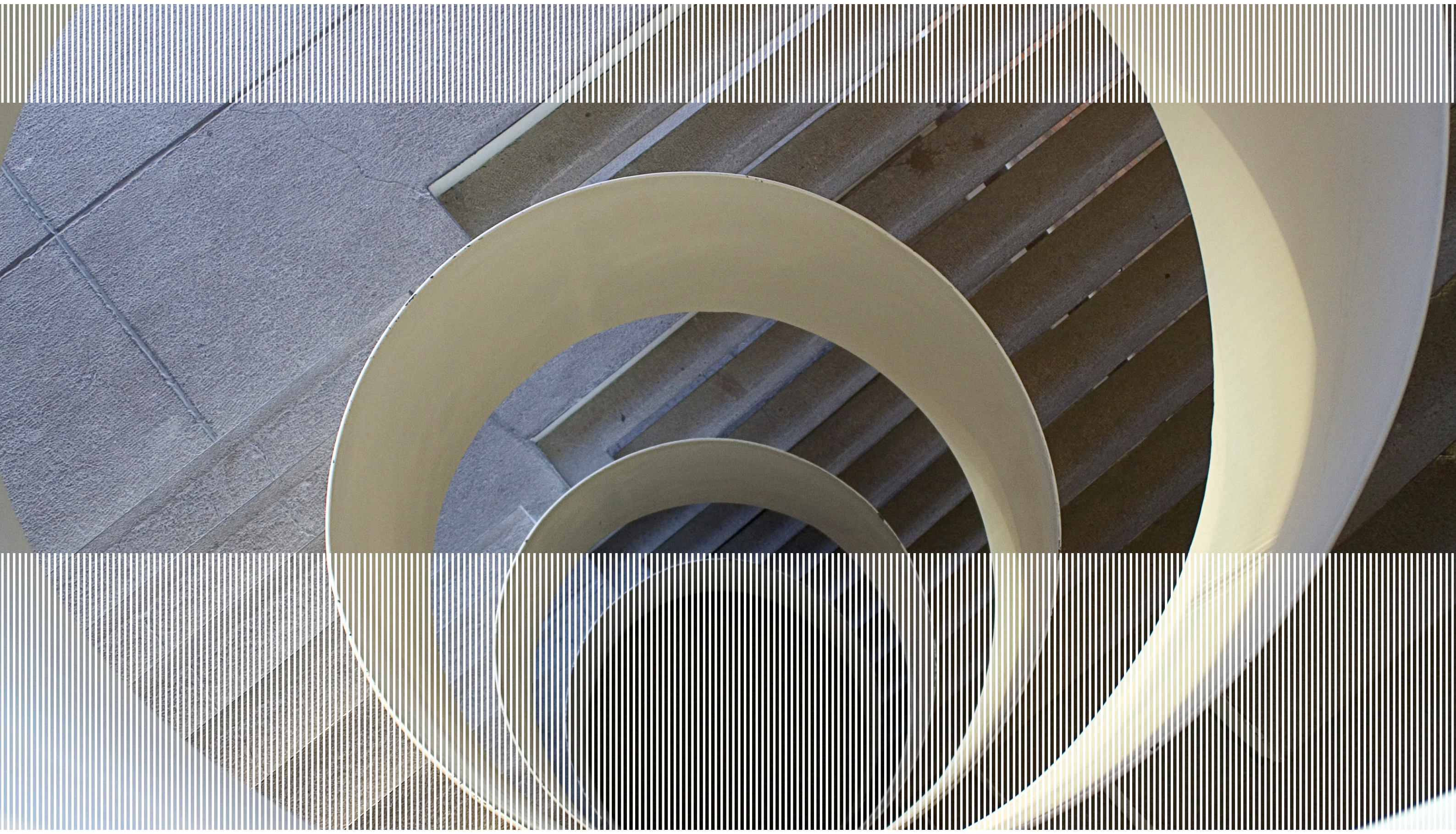

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