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**SINTEF Building and Infrastructure** Klaartje De Weerdt and Hedda Vikan

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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 Hammer
Centre Manager

## Summary

The use of Self Consolidating Concrete (SCC) can lead to improved working environment, and better form filling and surface finishing. However, its use is limited due to the low robustness regarding stability, especially for low grade concrete e.g. NS-EN 206-1 M60 B30. This report builds further on the findings published in a previous COIN report in which the reference SCC on the verge of instability is stabilized with either filler or chemical stabilizers, and the effect of stabilization on the stability and the rheology of the SCCs is investigated. In this study the combination of fillers and admixtures to stabilize SCC is included.

The combination of fillers and chemical stabilizers increases the viscosity of both matrix and concrete compared to the reference. In addition, they lead to an increased yield stress and viscosity of the matrix. The stability, however, does not seem to be improved compared to using either filler or chemical stabilizer to stabilize the SCC.

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# 1 Introduction

Self Consolidating Concrete (SCC) is a category of concrete which is able to flow under its own weight, fill the required space or formwork completely and produce a dense and adequately homogeneous material without the need for compaction (De Schutter et al. 2008). Although the use of SCC can provide an improved working environment, and better form filling and surface finishing, SCC currently holds less than 5% of the cast-in-place concrete in Norway. One of the major reasons leading to the limited acceptance of SCC by the building industry is the lack of robustness of SCC regarding stability, especially for low grade concrete e.g. NS-EN 206-1 M60 B30 (Kristiansen 2011). This type of SCC is generally more sensitive to variations in production e.g. water content of sand, resulting in the need for stricter quality control and possibly rejection of concrete on-site.

There are two common ways to improve the stability of SCC, either by adding chemical stabilizers or by adding filler. In a previous study, the effect of the different methods of stabilization on the rheological properties was investigated (Vikan and De Weerdt 2010).

This report builds further on the findings reported in (Vikan and De Weerdt 2010), in which the reference SCC on the verge of instability is stabilized with either filler or chemical stabilizers. In this study we include the combination of fillers and admixtures to stabilize SCC. The documentation of the materials and techniques, and the results obtained on stabilization with either filler or admixture are therefore taken over from the previous report.

# 2 Experimental

## 2.1 Materials

EN 197-1-CEM II/A-V 42,5 R Portland fly ash cement was used for all experiments. The cement had a Blaine fineness of 450 $m^2/kg$ and density of 3010 $kg/m^3$
Gneiss/Granite aggregates of following fractions were used:

- 0/8 mm sand, 111-curve (internal notation), Årdal
- 8/16 mm stone, Årdal

Filler (< 0.125 µm) sieved from the 0/8 mm sand was used to prepare concrete equivalent matrix.
Three powdered materials have been used as stabilizers. Sieve curves are given below:

- Limestone powder (Norcem) of density 2700 $kg/m^3$ and Blaine 360 $m^2/kg$ with abbreviation "LS"
- Filler sieved from non-washed, crushed 0/8mm Årdal sand, with density of 2730 $kg/m^3$ andbbreviation “C”.
- Filler produced from the same material as crushed 0/8 mm sand. The sand was thereafter sieved to obtain the 0/2 mm fraction, washed and sieved once more to obtain a filler with density of 2730 $kg/m^3$. It was abbreviated “W”.
-

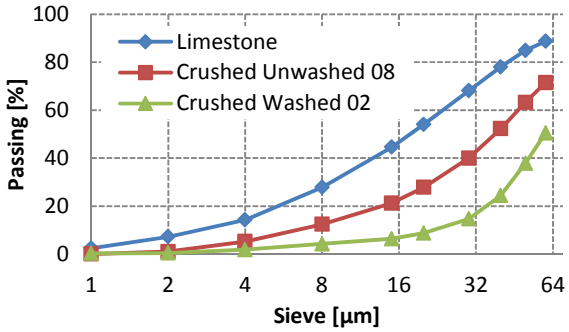


**Figure 1:** Sieve curves for powdered materials used in the study as stabilizers.

In addition silica fume (SF) was tested as a stabilizer in combination with chemical stabilizers.

The following chemical stabilizers have been used for the experiments:

- S1 is based on a polymer with high molecular weight. Dry solids: 2.2%. Active ingredients: 5.5%. Normal dosage is 1-4 $l/m^3$ concrete corresponding to 0.3-1.2% of cement weight. Initial dosage used for the experiments was 0.4% to avoid over dose of superplasticizer (SP).
- S2 is based on cellulose derivate that according to the producer produce thixotropic properties of the concrete. Normal dosage is 1-2 litre per 100 kg powder (d < 0.125 mm) corresponding to approximately 1-2% of cement weight. Initial dosage used for the experiments was 1% to avoid over dose of SP.

The following superplasticizers were used:

- SP1 is an acrylic polymer with 30% dry solids. It is a splitting type admixture (i.e. no stabilizing properties) and normal dosage is 0.3-1.2% of cement weight.
- SP2 is anacrylic polymer with 20.5% dry solids. It is a splitting type admixture with short open time.

SP2 has lower molecular weight, longer side chains and higher charge density than SP1. These properties result in higher degree of sterical hindrance (i.e. long side chains) and rapid slump loss (adsorbs quickly on the cement particles due to high charge density and relatively low molecular weight).

A set retarder based on Gluconat was added to all concretes at a dosage of 0.4% in order to eliminate the effect of hydration on the rheological measurements. Note that this product also has a water reducing effect.

## 2.2 Concrete experimental set-up

### 2.2.1 Recipes

The basis of the test matrix is a low grade concrete (M60 according to NS-EN 206-1) with an aimed slump flow of 675 ± 15 mm. The reference concrete is designed in order to be on the verge of separation (i.e. instability).
The SCC was stabilized in three ways:

- The mineral fillers were added in two dosages, namely 40 kg/m$^3$ (filler-to-cement ratio 0.12) and 80 kg/m$^3$ (filler-to-cement ratio 0.24).
- The chemical stabilizers were added in two different dosages: the minimum and maximum recommended dosage given by the producer.
- The mineral filler (filler-to-cement ratio 0.12) was also combined with chemical stabilizer (minimum recommended dosage).

In all cases the superplasticizer dosage was adjusted in order to keep the slump flow unchanged.
The concrete mix design is given in Table 1. The sieve curves of the sand and aggregates are given in the appendix. The chemical stabilized concretes have the same composition as the reference accept for the dosage of chemical stabilizer.
The experimental matrix is given in Table 2. The coloured rows are the mixes performed in addition to what was reported in (Vikan and De Weerdt 2010). It should be noted that a new cement batch was used for these additional mixes. To evaluate the impact of using a new cement batch, a second reference mix (REF 2) was measured for the concretes and pastes plasticized with SP1.

**Table 1:** Concrete mix design

| | Reference | 40 kg/m$^3$ Filler | 80 kg/m$^3$ Filler |
|---|---|---|---|
| **w/c** | 0.58 | 0.58 | 0.58 |
| **w/p** | 0.46 | 0.44 | 0.40 |
| **f/c (%)** | - | 12 | 24 |
| **Matrix (l/m$^3$)** | 325 | 338 | 352 |
| **Paste (l/m$^3$)** | 300 | 314 | 328 |
| **Cement (kg/m$^3$)** | 326 | 326 | 326 |
| **0/8 mm (kg/m$^3$)** | 1089.6 | 1067.1 | 1043.8 |
| **8/16 mm (kg/m$^3$)** | 725.0 | 711.4 | 695.9 |

**Table 2:** Experimental matrix

| Name | Filler stabilizer [% of cement weight] | Chemical stabilizer [% of cement weight] |
|---|---|---|
| **REF 1** | - | - |
| **REF 2** | - | - |
| **0.4% S1** | - | 0.4 |
| **1.2% S1** | - | 1.2 |
| **1.0% S2** | - | 1.0 |
| **2.0% S2** | - | 2.0 |
| **12% LS** | 12 | - |
| **24% LS** | 24 | - |
| **12% W** | 12 | - |
| **24% W** | 24 | - |
| **12% C** | 12 | - |
| **24% C** | 24 | - |
| **0.4% S1 + 4% SF** | 4 | 0.4 |
| **1.0% S2 + 4% SF** | 4 | 1.0 |
| **0.4% S1 + 12% W** | 12 | 0.4 |
| **1.0% S2 + 12% W** | 12 | 1.0 |
| **0.4% S1 + 12% LS** | 12 | 0.4 |
| **1.0% S2 + 12% LS** | 12 | 1.0 |

### 2.2.2 Mixing procedure

A forced pan mixer with a volume of 50 litres from Eirich was used to prepare the concretes. The volume of the concretes batches was 40 litres. The concretes were prepared by:

- 1 minute dry mixing of powders and aggregates
- 2 minutes while adding mixing water and half the amount of superplasticizer (previously intermixed with the water) and the full amount of chemical stabilizer and retarder
- 2 minutes pause/rest
- 2 minutes mixing with addition of remaining superplasticizer until aimed slump flow value was reached

### 2.2.3 Measurements

Air content and fresh concrete density was measured according to NS-EN 12350-7, 10 minutes after water addition.

**Rheology**

Slump flow and $T_{500}$ were measured according to EN 1235080: 2010 10 and 60 minutes after water addition. $T_{500}$ is measured as the time needed for the concrete to reach a diameter of 500 mm as the slump cone is lifted. Slump flow and $T_{500}$ are popular methods since they are quick, simple and can be performed simultaneously. The concrete was remixed for 1 minute before the 60-minutes measurements.
The slump flow was related to yield stress according to the equation derived by (Roussel et al. 2005):
$\tau_{y,SF} = \frac{225 \cdot \rho \cdot g \cdot V^2}{128 \cdot \pi^2 \cdot R^5}$ where R is the spread radius and V is the sample volume (6 liters)
Torque (T) was measured simultaneously with the slump flow (10 and 60 minutes after water addition) by aid of a ConTec Rheometer-4SCC. The measurement setup (with 4 measuring points per s) and the rotary vane are illustrated by Figure 2.

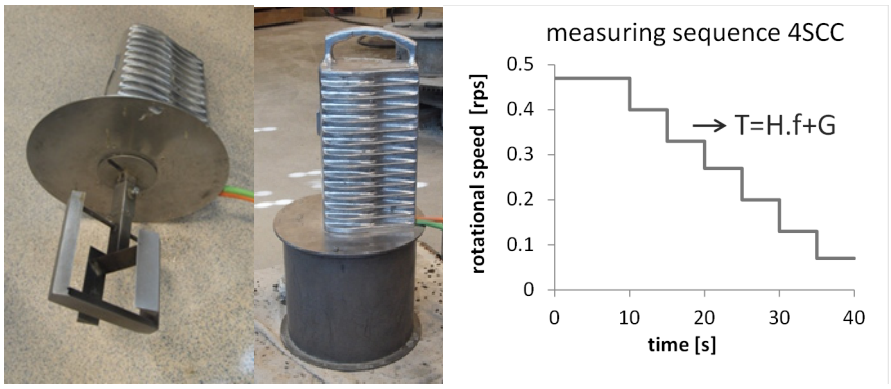


**Figure 2:** Rotary vane of the ConTec Rheometer-4SCC

By making a linear regression of the measured torque values the rheological properties G (A) and H (A·s) were obtained as the intersection with the ordinate and the slump of the line respectively. These values can theoretically be translated into the Bingham parameters yield stress ( $\tau_y$) and plastic viscosity ($\mu_p$). However, due to the complicated geometry of the rotary vanes of the ConTec Rheometer-4SCC, there are currently no equations or programs available for the conversion of G and H to $\tau_y$ and $\mu_p$. Values of G and H are therefore used throughout this report.

**Stability**

The sieve segregation index (SI) test was performed after 10 and 60 minutes. For this test about 10 l 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 of concrete from the container is poured upon the sieve (5 mm). The exact mass of the concrete poured onto the sieve is recorded, $m_s$. The concrete Is left for about 2 minutes and the sieve, after which the mass of the concrete passed through the sieve is determined ($m_{ps}$). The sieve segregation index is than:

——————— for

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

Visual Segregation Index (VSI) was also determined 10 and 60 minutes after water addition. VSI was measured on fresh concrete within the mixer ($VSI^m$) and on the flow board ($VSI^b$) after determination of slump flow. Table 3 shows the VSI rating within the mixer.
Table 4 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 3:** $VSI^m$ measured directly after 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 4:** 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 |

**Compressive strength**

Cubes (100x100x100mm) were cast 60 minutes after water addition for determination of compressive strength. The cubes were all cast in one pour without compaction or vibration. The forms were covered with plastic and cured in laboratory atmosphere for 24 hours. The samples were thereafter de-moulded and cured in water bath until time of testing. Compressive strength was measured according to NS-EN 12390-3:2009 after 7, 28 and 90 days of curing.

### 2.2.4 Repeatability

Repeatability of fresh concrete measurements was measured by producing the SP2-reference mix three times and thereafter measuring the fresh concrete properties. The results are reported in (Vikan and De Weerdt 2010). The main conclusions were the following:

A major drawback of $T_{500}$ measurements are short flow times (only a few seconds) for very flowable concretes and thus relatively low degree of accuracy [De Schutter et al. 2008]. The standard deviation of these $T_{500}$ measurements is, however, satisfactorily (only 3.4%).

The standard deviation of G and H are very high, corresponding to 19% and 37% respectively. This result is to be expected since the mixes are on the verge of separation and a homogeneous sample is of utmost importance for a reliable result. The low reproducibility of the G and H measurements indicate that these measurements are indicative and should not be used to quantify absolute differences within the test matrix.

## 2.3 Matrix experimental set-up

### 2.3.1 Recipes

The water-cement ratio was 0.45 for all mixes. All pastes were added 0.4% sodium gluconate per cement weight in order to limit effects of early hydration. Total paste volume was 200 ml.
The mixes were designed as concrete equivalent matrices. The pastes were thus added filler sieved from the 0/8 mm sand. The basis for the matrix recipes are given in Table 5. Experimental matrix is the same as the one for concrete (see Table 2).
Concrete equivalent superplasticizer dosages were used for the main test series. In order to eliminate the effect of variable superplasticizer dosage within the test series, additional test series were made for which it was kept constant: 0.8% for SP1 and 0.7% for SP2.

**Table 5:** Basis of matrix recipes

| | Reference/ Chemically stabilized | Filler dosage 1 | Filler dosage 2 |
|---|---|---|---|
| **Cement (g)** | 184.7 | 175.5 | 167.2 |
| **Water (g)** | 73.9 | 70.2 | 66.9 |
| **Filler (0/8 sand) (g)** | 37.0 | 34.5 | 32.1 |
| **Filler (stabilizer) (g)** | 0.0 | 21.1 | 40.1 |
| **Gluconate (%)** | 0.4 | 0.4 | 0.4 |

### 2.3.2 Mixing procedure

The matrices were blended in a high shear mixer from Braun (MR5550CA). The blending was performed by adding solids to the water and liquid admixtures (superplasticizer, retarder and stabilizer), mix for ½ a minute, rest for 5 minutes and blend again for 1 minute.

### 2.3.3 Rheological measurement sequence

The rheological parameters of the paste were recorded by a parallel plate (1 mm gap, upper plate and lower plate serrated) rheometer MCR 300 from Physica. The rheometer temperature control was set to 20°C. The following measurement sequence started 10 minutes after water addition:

- 1 minute pre-shearing with constant shear rate ($\dot{\gamma}$) of 60 $s^{-1}$ to produce uniform initial conditions
- 1 minute rest without shearing
- Flow curve (hysteresis):
    - Stress ($\tau\tau$) – shear rate ($\dot{\gamma}$) curve with linear sweep of $\dot{\gamma}$ from 1 up to 100 $s^{-1}$ in 30 points lasting 6 seconds each
    - Stress ($\tau$ ) – shear rate ($\dot{\gamma}$) curve with linear sweep of $\dot{\gamma}$ from 100 down to 1 $s^{-1}$ in 30 points lasting 6 seconds each
- Thixotropy:
    - $\dot{\gamma}$ = 0.1 in 10 measuring points each lasting 12 seconds (level 1)
    - $\dot{\gamma}$ = 250 in 5 measuring points each lasting 6 seconds (level 2)
    - $\dot{\gamma}$ = 0.1 in 50 measuring points each lasting 3.6 seconds (level 3)
- 10 seconds rest
- Shear rate ($\dot{\gamma}$) - stress ($\tau$) curve with logarithmic sweep from 0.5-250 Pa in 28 points each lasting 5 seconds in order to measure the gel strength
- 1 minute rest
- Static yield stress: $\dot{\gamma}$ = 0.02 $s^{-1}$ in 60 points each lasting 2 seconds

The thixotropy value is calculated as structure build up by substracting minimum viscosity (equilibrium value) in thixotropy level 2 from the maximum/peak viscosity (equilibrium value) in thixotropy level 3.

Full mixing and measurement sequence applied on the matrices are illustrated by Figure 3.

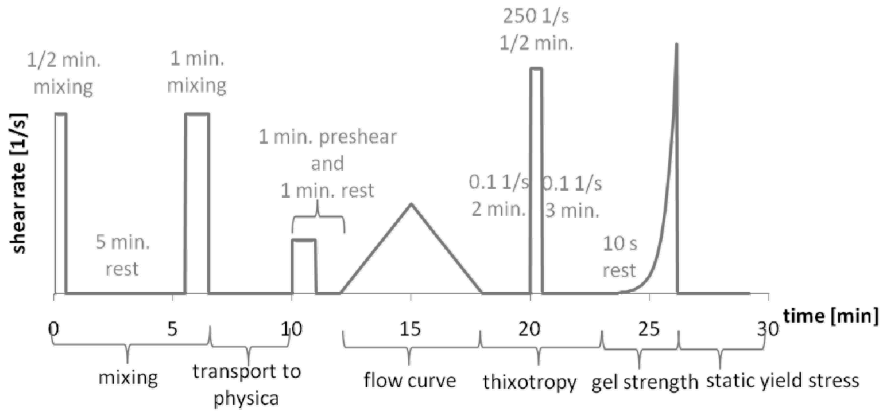


**Figure 3:** Mixing and measurement sequence of matrix

### 2.3.4 Repeatability

Repeatability of the rheological measurements was determined by measuring the rheological properties of three identical matrices, all with 0.60% SP2 of cement weight and limestone-cement mass ratio of 0.24. All pastes were stable. The results are reported in (Vikan and De Weerdt 2010). The main conclusions were the following:

The repeatability of viscosity, thixotropy value and static yield stress is considered to be satisfactory (standard deviation < 6%). Gel strength values are linked to considerably higher uncertainty than the other parameters (standard deviation of 12%). The yield stress values can be negative due to artefacts of the Bingham model that occur due to curvature of the flow curve. This also introduces a relatively high variation in the results (standard deviation of 18%). Such matrices could in effect be evaluated to have yield stress values approximately equal to zero.

# 3 Results

## 3.1 Fresh concrete properties

Fresh properties and rheological properties of concretes plasticized with SP1and SP2 are tabulated in Appendix A1. The results are presented in bar diagrams in the following paragraphs to facilitate discussion.

### 3.1.1 Rheology and stability of concretes plasticized with SP1

The dosages of SP1 used for the different SCCs are shown in Figure 4. The corresponding slump flows measured 10 and 60 minutes after water addition are shown in Figure 5. It can be seen that the SP1 dosages resulted in a slump flow after 10 minutes within the targeted range of 675 ± 15 mm, except for a few SCCs which were slightly overdosed and had a somewhat higher slump flow. The SCCs stabilized with chemical stabilizer and silica fume tended to require a higher dosage of SP1 than the filler stabilized ones.

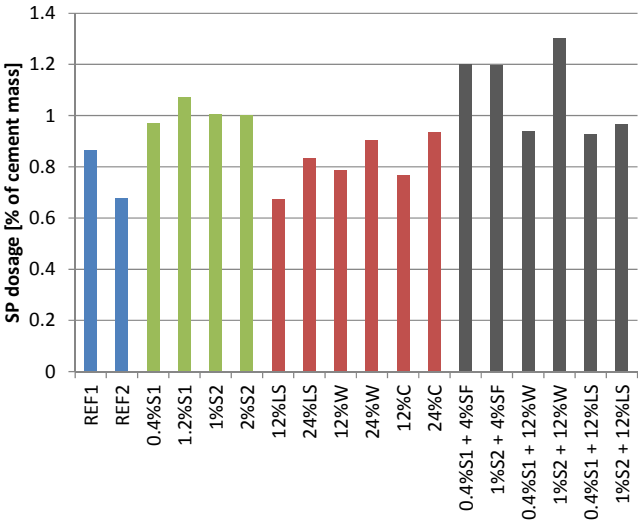


**Figure 4: Dosage of SP1 needed to obtain a SF of 675 ± 15 mm, 10 minutes after water addition.**

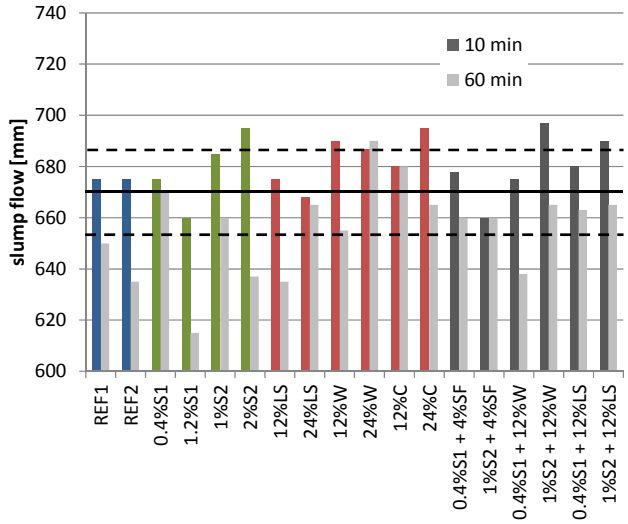


**Figure 5: Slump flow of the SCCs prepared with SP1, 10 and 60 minutes after water addition. Horizontal lines reflects target 675 ± 15 mm.**

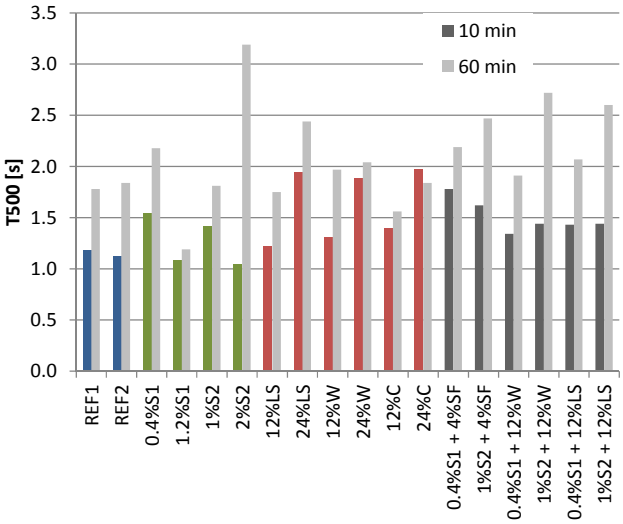


**Figure 6: T500 of the SCCs prepared with SP1, 10 and 60 minutes after water addition**

The flow time, T500, shown in Figure 6 relates to the viscosity of the SCCs. The T500 values indicated that the viscosity increased with the addition of fillers and/or chemical stabilizers. The highest viscosity was obtained for the SCCs stabilized with the higher filler dosage (24% of cement weight). A differentiation between the effect of the different fillers was, however, not possible.

When comparing the slump flow and T500 10 minutes and 60 minutes after water addition, generally a decrease in slump flow and an increase in T500 can be observed. This is a result of the structural build up within the SCCs during that time span. The slump loss was especially marked for the concretes stabilized with the higher dosage of chemical stabilizer. The marked slump loss of the 12% LS SCC might be attributed to the relatively low SP1 dosage. The increase of the T500 with time is most marked for SCCs containing the chemical stabilizer S2.

The visual segregation indices (VSI) of the mixes with SP1 are illustrated in Figure 7 and Figure 8. The VSI is generally higher in the mixer. This might be due to the fact that the concrete layer in the mixer is thicker than on the board allowing the larger aggregates to sediment more. $VSI^m$ indicates that only mixes with limestone powder (LS), washed fines (W) and the highest dosage of the chemical stabilizer S2 are deliverable concretes. $VSI^f$ illustrates, on the other hand, that all mixes except for the reference, the SCCs stabilized with chemical stabilizer S2 and lowest dosage of crushed fines (C) are deliverable. The fact that the SCC with 1% S2 + 12% W is ranged unacceptable might be due to an overdose of SP1 (see Figure 4). Summarized results from the two indices are that mixes with limestone filler (LS), washed fines (W) and the highest dosage of chemical stabilizer S1 are considered deliverable. In addition, it appears that combining filler and chemical stabilizer does not improve the stability.

The stability of the last series of mixes prepared was also assessed using the sieve segregation test. The results are shown in Figure 9. Ten minutes after water addition, the SCCs prepared with the chemical stabilizer S1 are ranged as segregation resistant except for the one with silica fume (SF). The SCCs prepared containing chemical stabilizer S2 are all ranged as questionably segregation resistant. Sixty minutes after water addition, the segregation resistance generally improves compared to the measurement after 10 minutes.

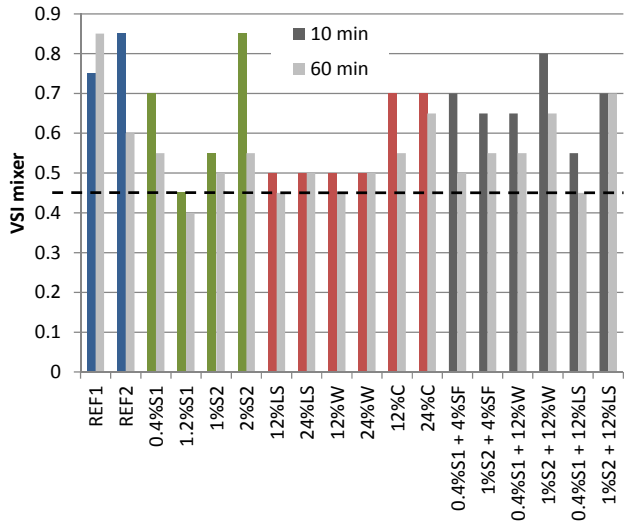


**Figure 7: The visual segregation index of SCCs prepared with SP1 in the mixer 10 and 60 minutes after water addition. The dashed horizontal line represents the upper limit of target range.**

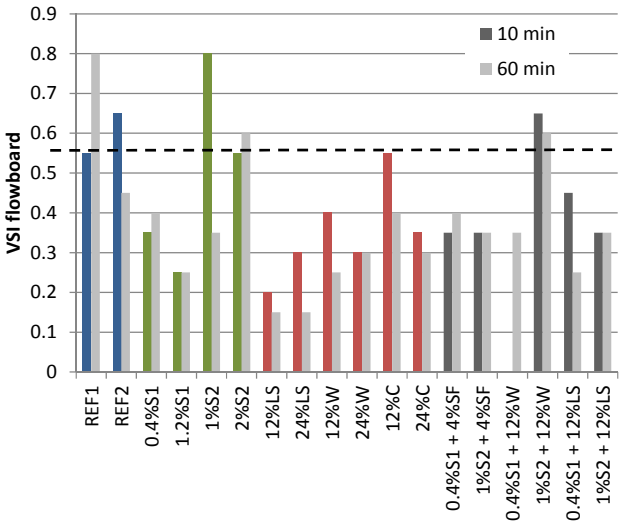


**Figure 8: The visual segregation index of SCCs prepared with SP1 on the flow board 10 and 60 minutes after water addition. The dashed horizontal line represents the upper limit of target range.**

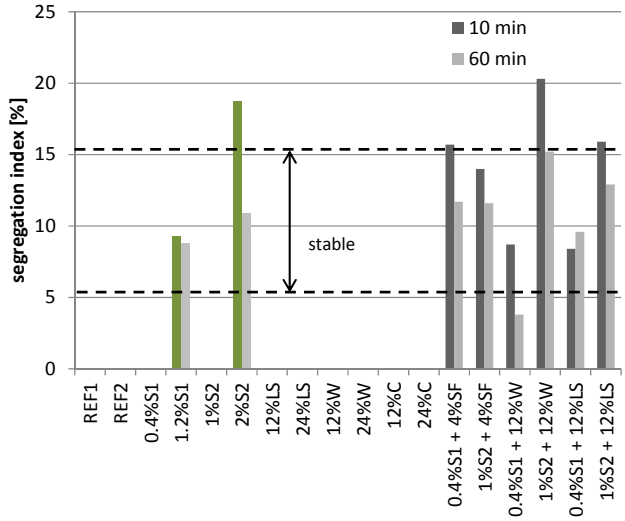


**Figure 9: The segregation index determined by the sieve segregation test on the most recently tested SCCs prepared with SP1, 10 and 60 minutes after water addition.**

Figure 10 and Figure 11 show respectively the parameters H and G from the rheological measurements with the ConTec Rheometer-4SCC at 10 and 60 minutes after water addition. Most of the tested SCCs are on the verge of stability; hence these results should be interpreted with care as the rheometer is not designed for analyzing segregating concrete. However, certain trends can be observed.
G generally decreases slightly with the addition of the chemical stabilizers and/or fillers, whereas H shows a slight increasing trend. When comparing the results after 10 and 60 minutes, the parameter H, related to viscosity, tends to increase slightly, which might be related to structural build up. For the yield stress related parameter G, on the other hand, there is no clear trend observed, as it both appears to increase and decrease with time. This is not in agreement with the slump flow loss observed in Figure 5.

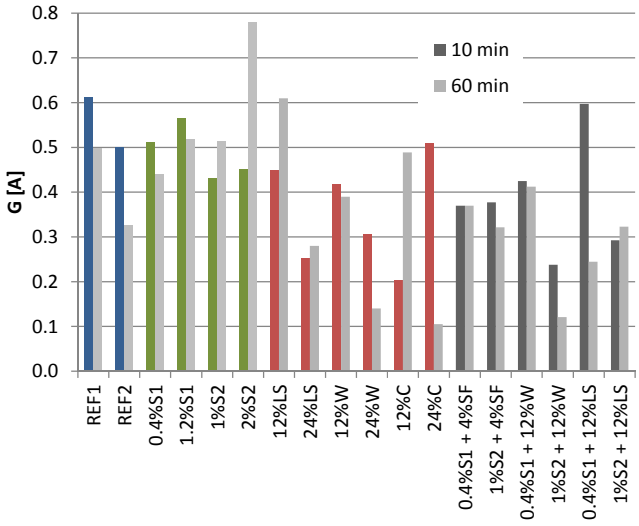


**Figure 10: The rheological parameter G related to the yield stress for the different tested SCCs prepared with SP1, 10 and 60 minutes after water addition.**

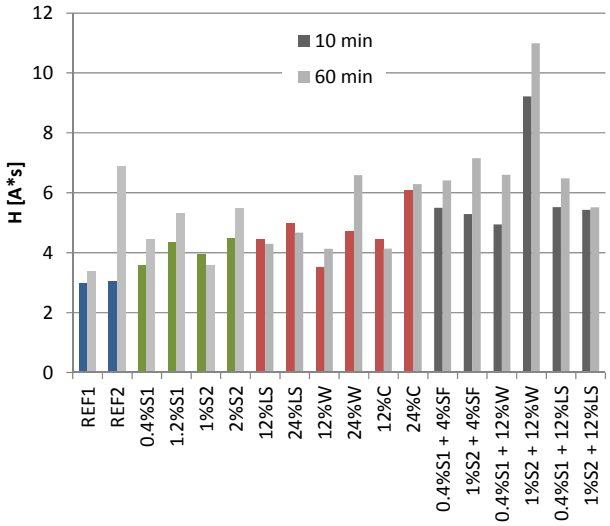


**Figure 11: The rheological parameter H related to the viscosity for the different tested SCCs prepared with SP1, 10 and 60 minutes after water addition.**

### 3.1.2 Rheology and stability of concretes plasticized with SP2

Concretes plasticized with SP2 experienced a marked slump loss 60 minutes after water addition in spite of the hydration being retarded. As a result, the concrete was no longer self-consolidating after 60 minutes and fresh concrete properties were only determined 10 minutes after water addition. It should also be noted that SCCs stabilized with lower filler dosages (12% of the cement weight) were not tested for SCCs prepared with SP2.

The dosages of SP2 used for the different SCCs are shown in Figure 12. The aim was to obtain a slump flow of 675 ± 15 mm 10 minutes after water addition. From Figure 13 it can be seen that all mixes had a slump flow within the targeted range, except for the mixes with 24% washed (W) or crushed (C) fines as well as the mix with 1% S2 + 12% LS as they were slightly overdosed with SP2 . The SCCs stabilized with the high dosage of chemical stabilizer or a combination with chemical stabilizer and filler required compared to the other mixes a higher dosage of SP2 to reach the targeted spread. The flow time T500, which is related to the viscosity of the concrete, increased upon stabilization. The most significant increase was observed for the SCCs stabilized with 24% washed (W) or crushed (C) fines.

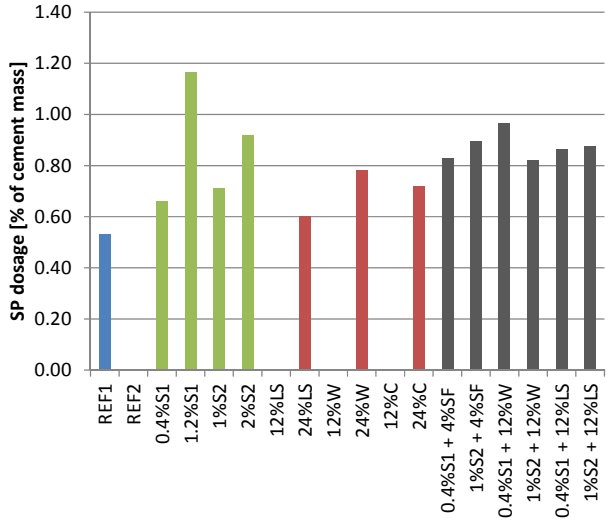


**Figure 12: Dosage of SP2 needed to obtain a slump flow of 675 ± 15 mm, 10 minutes after water addition.**

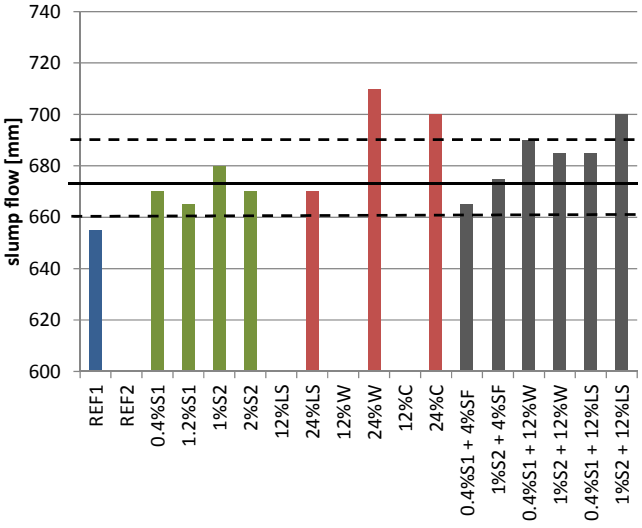


**Figure 13: Slump flow of the SCCs prepared with SP2, 10 and 60 minutes after water addition. Horizontal lines reflects target 675 ± 15 mm.**

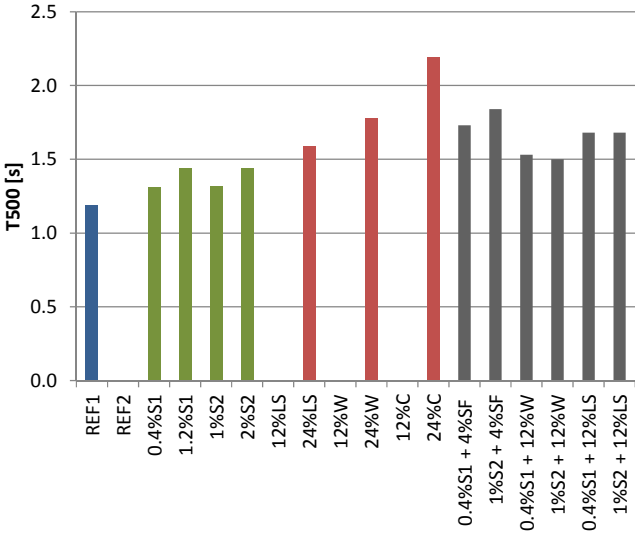


**Figure 14: T500 of the SCCs prepared with SP2, 10 and 60 minutes after water addition**

None of the tested combinations of stabilizers had a marked effect on the VSI measured in the mixer as illustrated in Figure 15. Furthermore, on the flow board all stabilized SCCs were graded equally stable or more unstable than the reference SCC as shown in Figure 16. The chemical stabilizer S2 and the combination of fillers and chemical stabilizer even rendered the SCC unacceptably unstable. This indicates that the SP2 dosage needed to reach the slump flow of 675 ± 15 mm for the tested SCCs was too high, so that it could not be stabilized with measures tested, hence the concretes were rated not deliverable when both $VSI^m$ and $VSI^f$ are taken into account

The results of the sieve segregation test (see Figure 17) indicate that only SCCs containing silica fume combined with chemical stabilizer or 1% S2 + 12% W are satisfactory segregation resistant. This corresponds relatively well with the VSI on the flow board except for the 1.2% S1 blend which was rated stable on the board, but not by the sieve test.

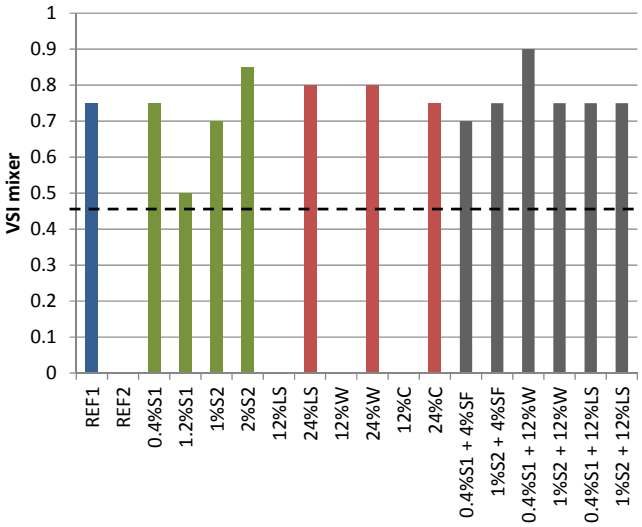


**Figure 15 The visual segregation index of SCCs prepared with SP2 in the mixer 10 and 60 minutes after water addition. The dashed horizontal line represents the upper limit of target range.**

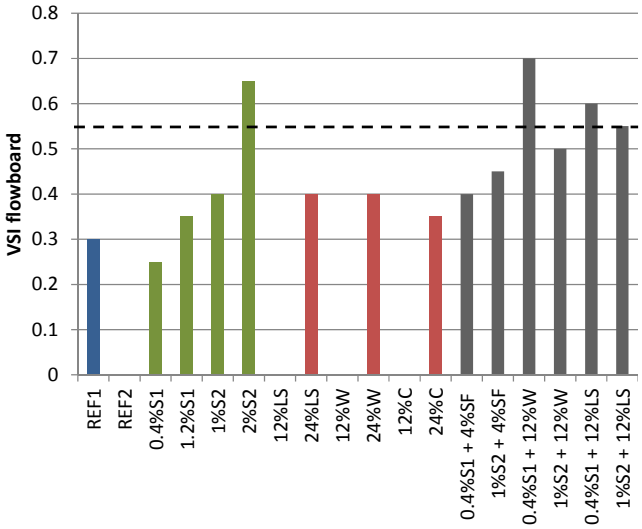


**Figure 16: The visual segregation index of SCCs prepared with SP2 on the flow board 10 and 60 minutes after water addition. The dashed horizontal line represents the upper limit of target range.**

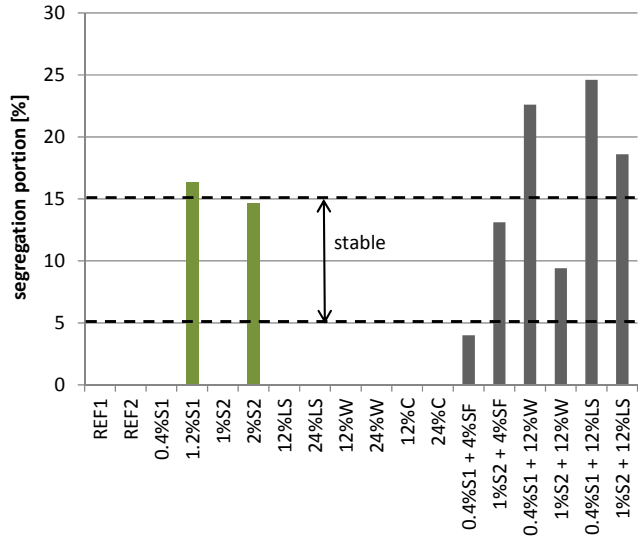


**Figure 17: The segregated portion determined by the sieve segregation test on the most recently tested SCCs prepared with SP2, 10 and 60 minutes after water addition.**

Figure 18 and Figure 19 show the rheological parameters G and H for the tested SCCs with SP2. The yield stress related parameter G appears to decrease upon stabilization. When comparing the different combinations of filler and chemical stabilizer, it can be observed that the blends with the lowest G are the ones which are rated the most unstable by both VSI[f] and the sieve segregation test. The viscosity related parameter H tends to increase upon stabilization, especially for the combinations of chemical stabilizer and filler.

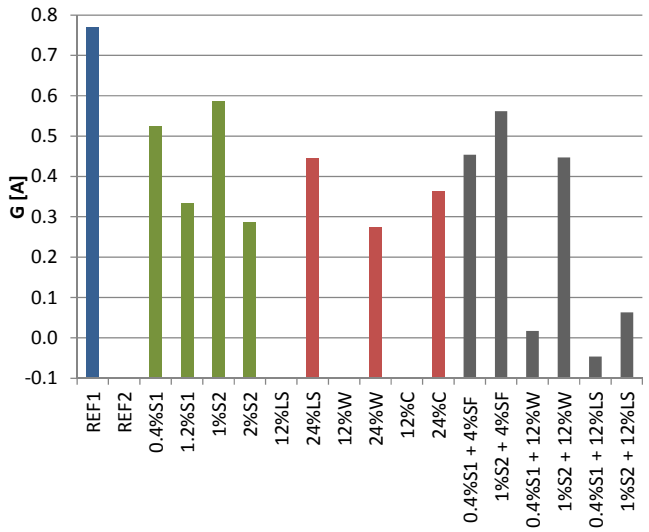


**Figure 18: The rheological parameter G related to the yield stress for the different tested SCCs prepared with SP2, 10 and 60 minutes after water addition.**

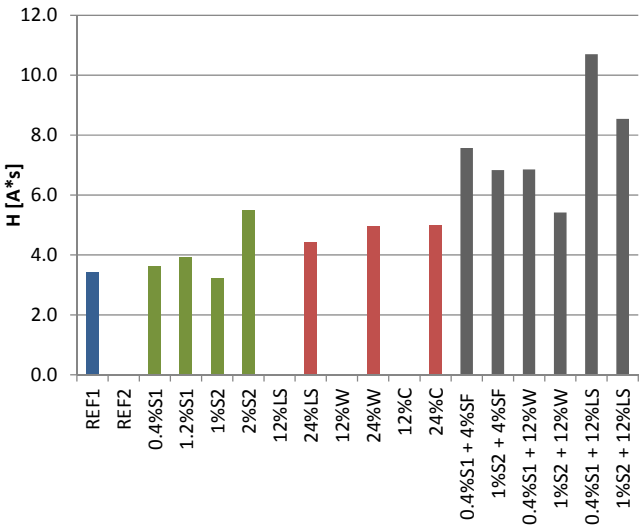


**Figure 19: The rheological parameter H related to the viscosity for the different tested SCCs prepared with SP2, 10 and 60 minutes after water addition.**

## 3.2 Fresh properties of matrix

The rheological properties of matrices plasticized with SP1and SP2 are tabulated in Appendix A1. The results are presented in bar diagrams in the following paragraphs to facilitate discussion.

### 3.2.1 Rheology of matrices plasticized with SP1

The Bingham parameters measured on concrete equivalent matrix plasticized with SP1 are given in Figure 20 and Figure 21. The yield stress increased with the addition of chemical stabilizers, indicating a structural build up. The higher filler addition (24% of the cement weight) on the other hand give rise to negative yield stress values. This negative yield stress is an artifact of the Bingham model caused by convex curvature of the flow curve, e.g. in the case of shear thickening which possibly can be attributed to the homogeinization of the matrix.

The plastic viscosity increased most clearly with addition of the higher amount of filler. This is inline with the Krieger-Dougherty equation which predicts an increase in viscosity with increasing volume fraction of solids (Krieger and Dougherty 1959). However, also the combination of silica fume with chemical stabilizer resulted in a clear increase in viscosity eventhough the solid volume does not increase as much as for the high filler blends. This indicates that silica fume contributes to a greater extent to the structural build up in the paste than the other fillers which is inline with the findings in (Vikan 2005). The plastic viscosity results correspond with measurements (T500) done on concrete. It should however be noted that the differences in plastic viscosity of pastes with the different fillers were too small to make any distinction between them.

The static yield stress and the thixotropy measured on matrices with concrete equivalent SP1 dosage are respectively given in Figure 22 and Figure 23. The higher dosage of both chemical stabilizer and the combinations of chemical stabilizer and filler or silica fume increase the static yield stress most considerably compared to the reference. A similar observation can be made regarding the thixotropy, however, in that case there is no clear difference between the lower and higher dosage of chemical stabilizer.

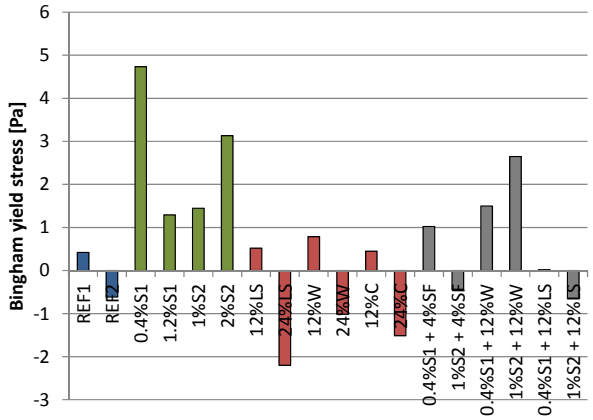


**Figure 20: Bingham yield stress of matrix with a concrete equivalent dosage of SP1.**

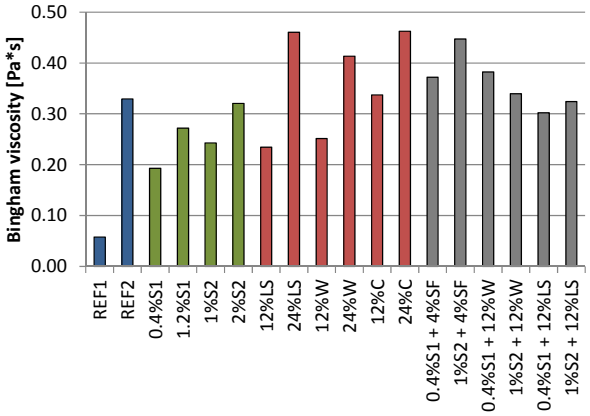


**Figure 21: Bingham viscosity of matrix with a concrete equivalent dosage of SP1.**

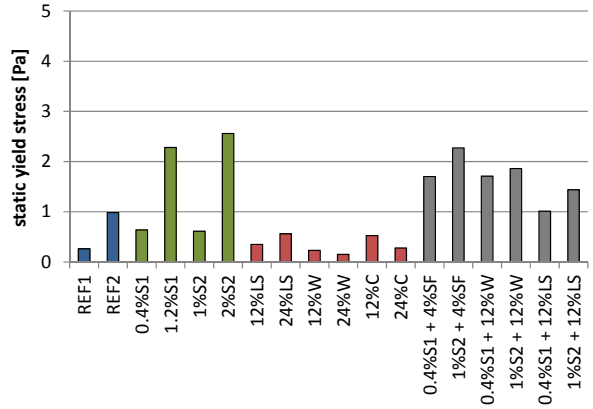


**Figure 22: Static yield stress of matrix with a concrete equivalent dosage of SP1.**

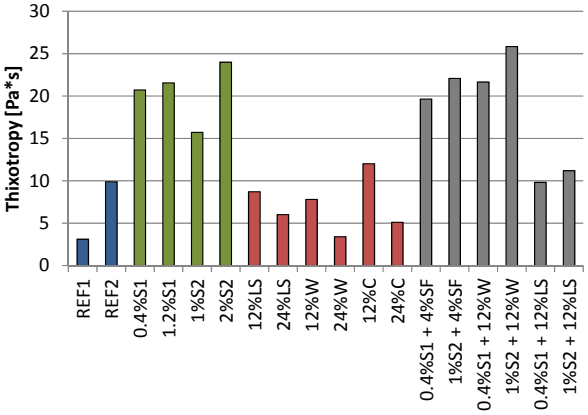


**Figure 23: Thixotropy of matrix with a concrete equivalent dosage of SP1.**

The rheological parameters were also measured on matrices with a constant SP1 dosage (0.80%) to eliminate the effect of varying the SP content. The plastic viscosity and static yield stress are respectively shown in Figure 24 and Figure 25. The other parameters are tabulated in the Appendix. Both the plastic viscosity and static yield stress measurements correlate well with the ones obtained on the matrices with concrete equivalent SP dosage. However, the static yield stress results indicate that the chemical stabilizer S2 has a greater impact than S1, which was not that clear for the concrete equivalent blends. It can also be seen that the combination of S2 with filler or silica fume increases the static yield stress even more than solely using chemical stabilizer.

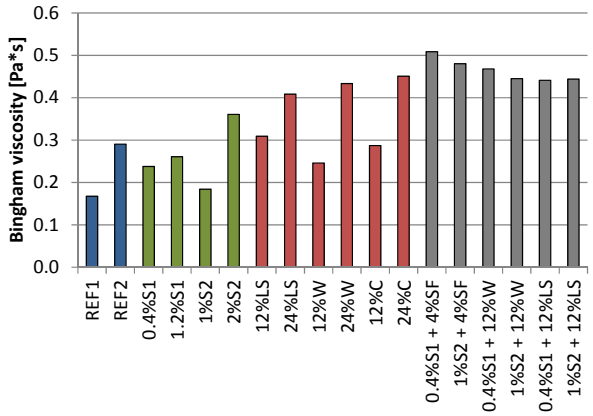


**Figure 24: Bingham viscosity of matrix with a constant dosage of SP1 (0.80%).**

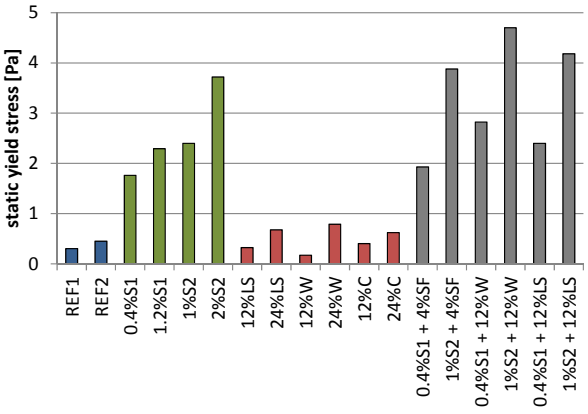


**Figure 25: Static yield stress of matrix with a constant dosage of SP1 (0.80%).**

### 3.2.2 Rheology of matrices plasticized with SP2

The Bingham parameters for the matrices prepared with a concrete equivalent SP2 dosage are shown in Figure 26 and Figure 27. More of the blends exhibited negative yield stress values which indicates that matrices prepared with concrete equivalent SP2 dosage have a greater tendency to exhibit shear thickening behaviour than for the ones prepared with concrete equivalent SP1 dosage. The plastic viscosity was most increased by the higher filler additions. The combination of filler or silica fume with chemical stabilizer also increased the viscosity, and this seemed to be independent of the type of filler or chemical stabilizer used.

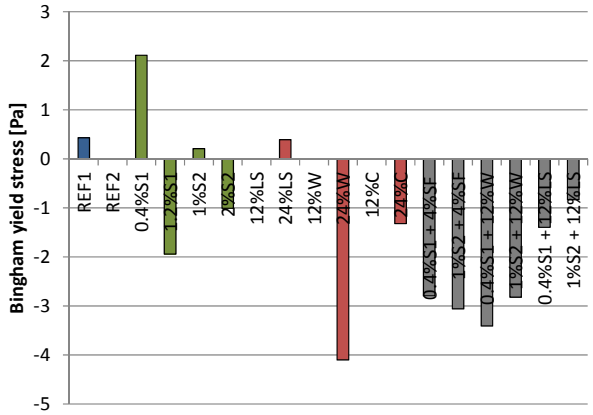


**Figure 26: Bingham yield stress of matrix with a concrete equivalent dosage of SP2.**

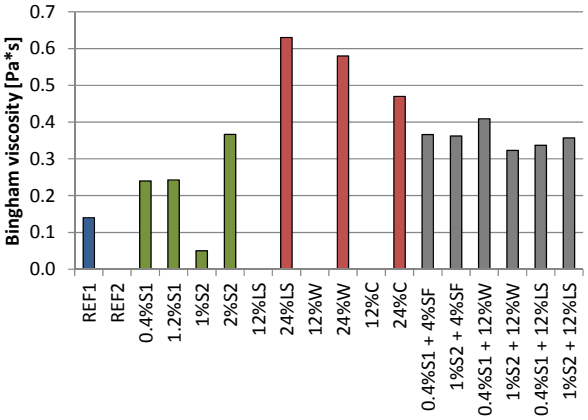


**Figure 27: Bingham viscosity of matrix with a concrete equivalent dosage of SP2.**

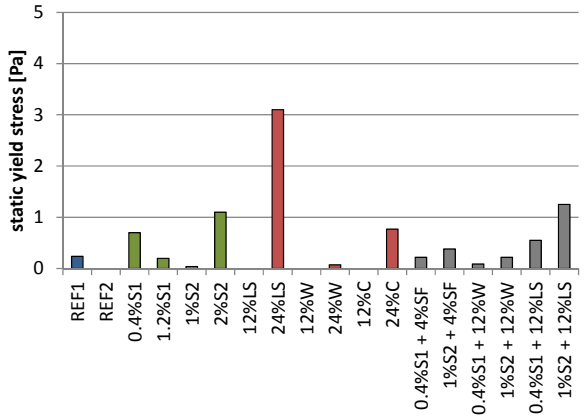


**Figure 28: Static yield stress of matrix with a concrete equivalent dosage of SP2.**

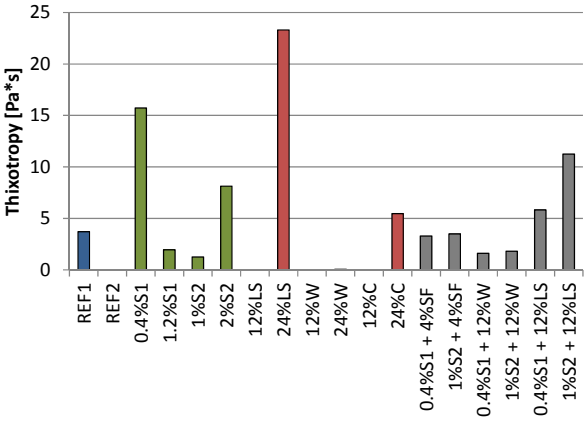


**Figure 29: Thixotropy of matrix with a concrete equivalent dosage of SP2.**

The static yield stress and thixotropy of the blends with concrete equivalent SP2 dosage (see Figure 28 and Figure 29) seemed to be most affected by the higher limestone addition. Some of the mixes with chemical stabilizers showed an increase in static yield stress and thixotropy, however, there were no clear trends regarding type and dosage.

At constant SP2 dosage, the static yield stress could be increased by the higher dosage of chemical stabilizers, the higher dosage of limestone powder (LS) or by a combination of the two (see Figure 31). When tested at concrete equivalent dosages of SP2, this effect might have been eliminated due to overdosing of the SP2 for the high dosage chemically stabilized mixes (see Figure 28).

When comparing Figure 27 and Figure 30, it is interesting to see that the observation regarding the plastic viscosity do not change that much whether concrete equivalent or constant SP2 dosages are used. The higher filler additions still have the strongest increasing effect, followed by the combination of fillers and chemical stabilizers. It should be noted once more that there are no clear trends regarding the effect of the type of filler.

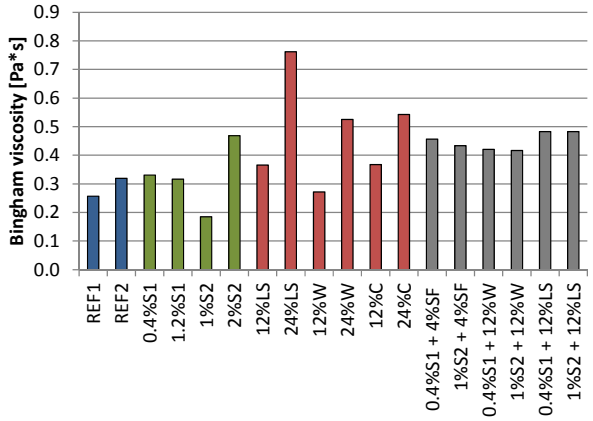


**Figure 30: Bingham viscosity of matrix with a constant dosage of SP2 (0.70%).**

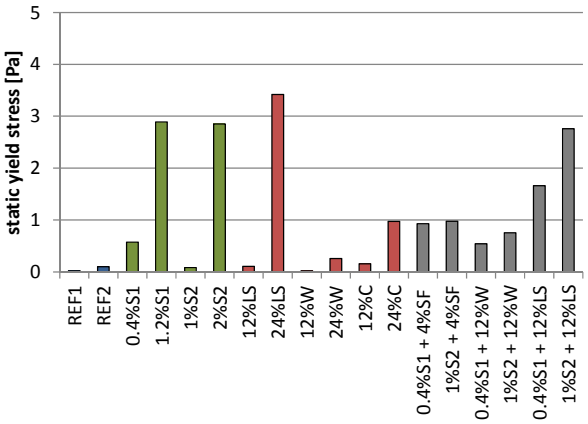


**Figure 31: Static yield stress of matrix with a constant dosage of SP1 (0.70%)**

## 3.3 Correlation between the measured parameters

### 3.3.1 Concrete parameters

Figure 32 shows the correlation between the viscosity related concrete parameters for the concretes prepared with SP1 and SP2: H from the ConTec Rheometer-4SCC and T500. The two parameters show a tendency to relate linearly, however with a large scatter which is also reflected in the low $R^2$ of 0.18.

The relation between the yield stress related parameters measured on concrete, G from the ConTec Rheometer-4SCC and the slump flow, can be seen from Figure 33. There is no clear relation between the two parameters. This can be expected as the concretes were designed to have a slump flow in a narrow interval (675 ± 15 mm).

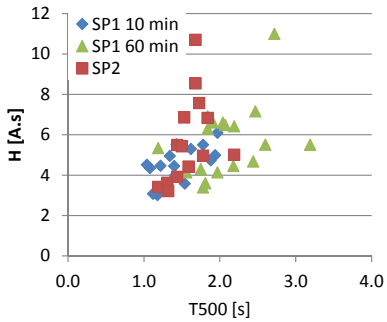


**Figure 32: Correlation between the viscosity related concrete parameters H and T500 ($R^2$=0.18).**

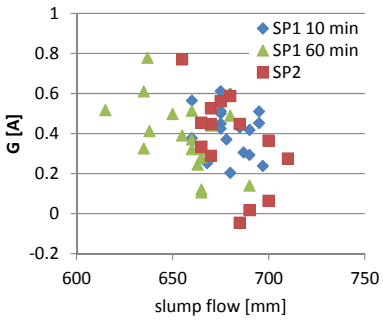


**Figure 33: Correlation between the yield stress related concrete parameters G and slump flow ($R^2$=0.21).**

### 3.3.2 Matrix parameters

The correlations between the different rheological parameters measured on matrix with concrete equivalent SP-dosage (c.e.) are shown in Figure 34 to Figure 36. It should be noted that some of the matrices showed a shear thinning behavior. For those mixes the Bingham model does not apply well and negative Bingham yield stresses can be obtained. It is therefore not surprising that the Bingham yield stress does not correlate well to the static yield stress as shown in Figure 34. The static yield stress relates, on the other hand, linearly to the gel strength and the thixotropic value, though with some scatter. The static yield stress, gel strength and thixotropy are all measures for the structural buildup of the matrix.

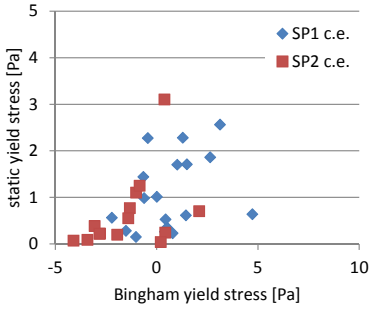


**Figure 34: Correlation between the static yield stress and the Bingham yield stress for matrix with a concrete equivalent SP dosage ($R^2$=0.21).**

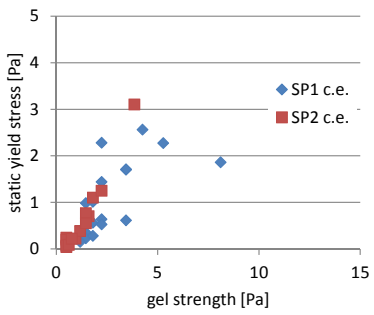


**Figure 35: Correlation between the static yield stress and the gel strength for matrix with a concrete equivalent SP dosage ($R^2$=0.55).**

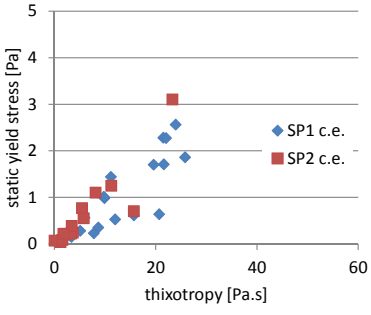


**Figure 36: Correlation between the static yield stress and the thixotropy for matrix with a concrete equivalent SP dosage ($R^2$=0.74).**

For the mixes with constant SP-dosage (Figure 37 to Figure 39) similar observations can be made as for the concrete equivalent mixes. The static yield stress even tends to correlate better with the gel strength and the thixotropic value.

The good correlation between the static yield stress and the thixotropy is remarkable as they are two different ways to measure the structural build up: The former is the maximum yield stress measured in the elastic domain at a constant shear rate and the latter is the difference in viscosity when shearing at a high and a low shear rate.

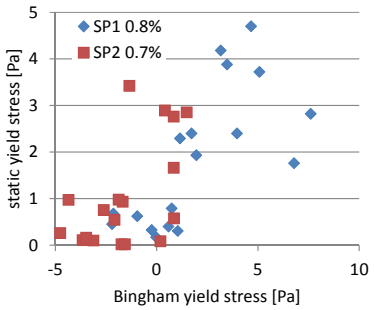


**Figure 37: Correlation between the static yield stress and the Bingham yield stress for matrix with a constant SP dosage ($R^2$=0.46).**

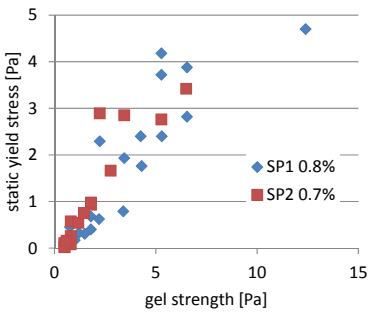


**Figure 38: Correlation between the static yield stress and the gel strength for matrix with a constant SP dosage ($R^2$=0.78).**

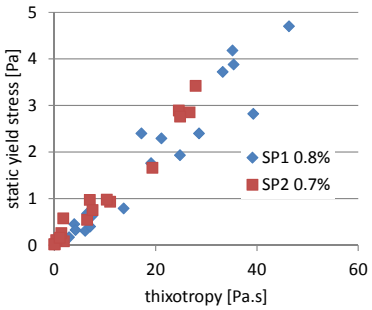


**Figure 39: Correlation between the static yield stress and the thixotropy for matrix with a constant SP dosage ($R^2$=0.93).**

### 3.3.3 Concrete vs. paste parameters

Figure 40 and Figure 41 show the correlation between the plastic viscosity measured on concrete equivalent matrix and the viscosity related parameters measured on concrete (T500 and H). The plastic viscosity tends to relate linearly to the T500, though with quite some scatter.

As previously mentioned, the measurements performed with the ConTec Rheometer-4SCC, and hence also the H values, should be interpreted with care as the instrument is not designed to investigate unstable concrete. This could explain why no clear trend can be observed when relating the plastic viscosity to the H (see Figure 41).

Figure 42 and Figure 43 show the correlation between the static yield stress measured on concrete equivalent matrix and the yield stress related parameters measured on concrete (SF and G). There is no clear correlation between the parameters which could be expected as the concretes were designed to have a slump flow in a narrow interval (675 ± 15 mm).

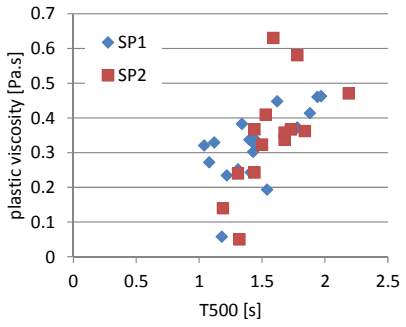


**Figure 40: Correlation between the T500 measured on concrete and the plastic viscosity measured on the concrete equivalent matrix ($R^2$=0.39).**

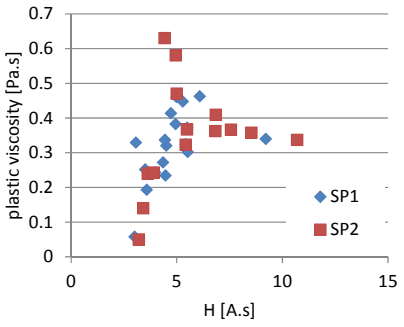


**Figure 41: Correlation between the H measured on concrete and the plastic viscosity measured on the concrete equivalent matrix ($R^2$=0.13).**

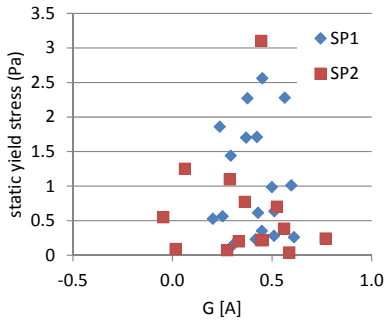


**Figure 42: Correlation between the G measured on concrete and the static yield stress measured on the concrete equivalent matrix ($R^2$=0.00).**

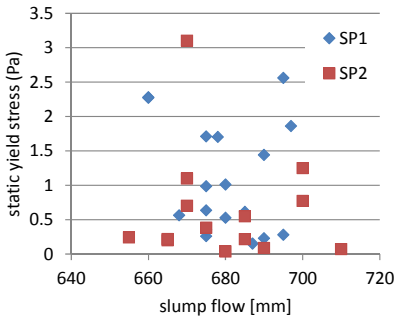


**Figure 43: Correlation between the slump flow measured on concrete and the static yield stress measured on the concrete equivalent matrix ($R^2$=-0.02).**

### 3.3.4 Stability parameters

In Figure 44 the VSI board is compared with the VSI mixer. In Figure 45 and Figure 46 the visual segregation index (VSI) is compared with the sieve segregation test (segregation index). The VSI mixer and VSI board has to be respectively lower than 0.45 and 0.55 to be considered acceptably stable. The segregated portion should be below 15% for the SCC to be considered satisfactory segregation resistant, above that the stability is questionable. The shaded boxes in the figures indicate the area in which concretes are ranged acceptably or satisfactory stable by both evaluation methods applied. It should be noted that the sieve segregation test was only performed for a selection of the SCCs as shown in Figure 9 and Figure 17.

From Figure 44 it can be seen that the VSI board underestimates the stability of the SCCs compared to the VSI mixer. This was also mentioned in section 3.1. Similar observation were reported by J.E. Wallevik in (Wallevik 2009).

From Figure 45 it can be seen that the VSI mixer tends to underestimate the stability of the SCCs compared to the sieve segregation test. The VSI board, on the other hand, appears to relate better to the segregation test as shown in Figure 46.

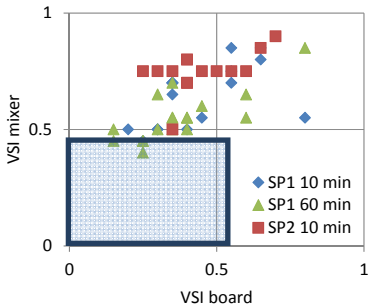


**Figure 44: Correlation between the two VSI measurements on concrete.**

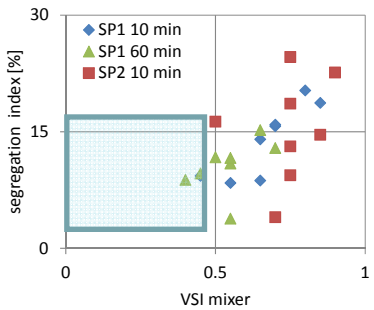


**Figure 45: Correlation between the segregation index and the VSI mixer.**

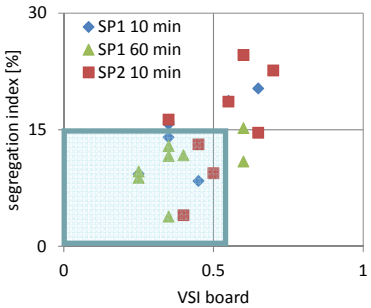


**Figure 46: Correlation between the segregation index and the VSI board.**

### 3.4 Concrete compressive strength

Compressive strengths of concretes plasticized with SP1 and SP2 are illustrated in Figure 47 and Figure 48 respectively.

In the case of SP1, the lower chemical stabilizer addition appears to be slightly beneficial for strength, whereas, the higher dosages result in a reduction in strength relative to the reference SCC. The addition of the fillers "C" and "W" result generally in a strength increase of about 10% after 28 and 90 days, but limestone powder appear to be the best filler regarding strength, giving rise to a strength increase of about 20% after 28 and 90 days. Similarly, when comparing the combinations of filler and chemical stabilizer, it can be seen that the limestone containing blends have a higher strength than the ones containing washed filler (W). Silica fume appears to have a beneficial effect on the strength after 28 and 90 days (8-14%).

For mixes prepared with SP2, there is no considerable impact of the chemical stabilizers on the strength. The filler additions, on the other hand, tend to increase the compressive strength (11-23% after 28 and 90 days). The combination of chemical stabilizer and silica fume or limestone powder resulted in a considerable strength increase (about 25% after 28 and 90 days), however, when the chemical stabilizer was combined with washed filler (W) there was hardly any effect on the strength (up to 5% after 28 ad 90 days) compared to the reference. This could be attributed to the lower fineness of the washed filler compared to the limestone powder which could result in worse packing and a lower nucleation surface. But, this is contradictory with the higher strength obtained by the mix with 24% washed filler compared to the one with 24% limestone filler.

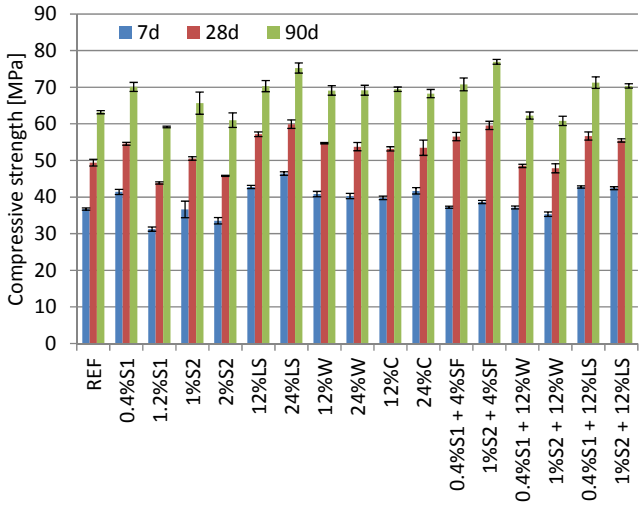


**Figure 47: Concrete compressive strength for mixes with SP1. Each value is calculated as an average and standard deviation of 3 cubes.**

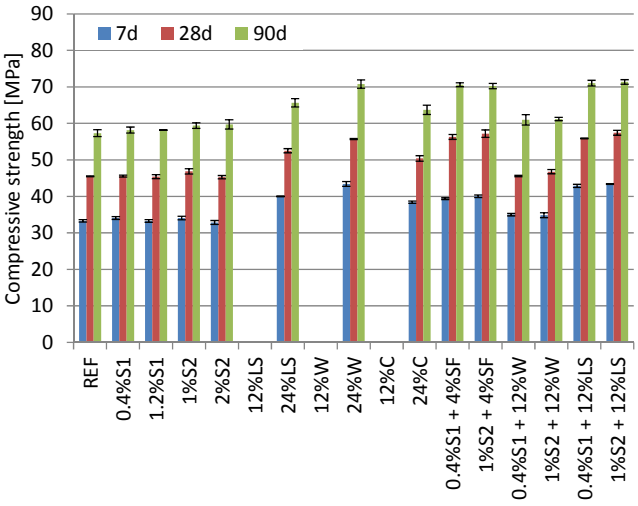


**Figure 48: Concrete compressive strength for mixes with SP2. Each value is calculated as an average and standard deviation of 3 cubes.**

# 4 General discussion

## 4.1 Stability

The stability of the tested SCCs was evaluated using the visual segregation index (VSI) both on the flow board and in the mixer, respectively abbreviated with $VSI^f$ and $VSI^m$. In addition, the sieve segregation test was performed for a selection of the SCCs. The $VSI^f$ seemed to overestimate the stability compared to the $VSI^m$. A study performed by J.E. Wallevik (Wallevik 2009) reported similar findings. Hence, the $VSI^m$ was considered to be the limiting one. However, the sieve segregation test which is a well established test method for stability appears to agree better with the $VSI^f$ than with the $VSI^m$.

The $VSI^m$ indicates that SCCs with SP1 stabilized with limestone filler (LS), washed fines (W) and the highest dosage of chemical stabilizer S1 can be considered stable enough to be used on site. The other stabilization methods did not appear to stabilize sufficiently. In addition, it appears that combining filler and chemical stabilizer does not improve the stability compared to using either one of them. The $VSI^f$ and the sieve segregation ranked all the tested SCCs with SP1 as sufficiently stable except for the SCC stabilized with only S2 and the one stabilized with 1%S2 + 12%W possibly due to over dosage of SP1.

None of the tested combinations of stabilizers improved the stability of SCCs with SP2 according to the $VSI^m$ evaluation, except for the high dosage of S1. This indicates that the SP2 dosage needed to reach the slump flow of 675 ± 15 mm for the tested SCCs was so high that the resulting SCCs could not be stabilized with measures tested regarding to the $VSI^m$.

It should be noted that the reference SCC plasticized with SP2 was ranged stable (0.3) according to the $VSI^f$. Upon stabilization, the stability of the SCC was maintained or reduced compared to the reference SCC. The results of the sieve segregation test indicate that only SCCs containing silica fume combined with chemical stabilizer or 1% S2 + 12% W are satisfactory segregation resistant. This corresponds relatively well with the $VSI^f$ except for the 1.2% S1 blend which was rated stable on the board, but not by the sieve test

## 4.2 Fresh and rheological properties of concrete and matrix

The stabilization methods tested affect the rheological parameters of the SCCs plasticized by SP1 or SP2 similarly. However, the extent of the effect depends on the type and dosage of plasticizer used. In the following some general findings for SCCs stabilized by SP1 and SP2 are discussed.

The SCCs stabilized with chemical stabilizers or a combination of chemical stabilizers and fillers (including SF) tended to require a higher dosage of SP to reach the targeted slump flow than the purely filler stabilized SCCs. This can be attributed to the fact that the chemical stabilizers give rise to a higher structural build up, which is reflected in an increase in yield stress and hence with a decrease in the slump flow. The slump flow is kept in the targeted interval by increasing the SP dosage. This means that when using chemical stabilizers a balance needs to be found between the SP and chemical stabilizer dosage. The increase in structural build up upon chemical stabilizer addition is confirmed by the matrix results showing an increased yield stress and thixotropy. Stabilizer S2 seems to give rise to a slightly higher structural build up than S1 when combined with SP1. It should be noted that silica fume can also contribute to the structural build up at early age (Vikan 2005), however due to the low levels of silica fume used in this series (4% of the cement weight) no clear effect was observed.

The viscosity of the stabilized SCCs, indicated with the T500 values, increased with the addition of fillers and/or chemical stabilizers. The highest viscosity was obtained for the SCCs stabilized with the higher filler dosage (24% of cement weight), which is confirmed by the matrix results. A differentiation between the effect of the different fillers was, however, not possible.

A combination of chemical stabilizers and fillers also tends to increase the viscosity, but as they at the same time increase the yield stress and therefore require a higher SP dosage, the effect is not that clear for SCCs and c.e. matrix.

The parameters H and G from the rheological measurements with the ConTec Rheometer-4SCC did not correlate well with any of the other measured parameters. This is due to the fact that most of the tested SCCs are on the verge of stability; and the rheometer is not designed for analyzing segregating concrete. In general stabilization of SCC resulted in a decrease of G and an increase in H (respectively related to yield stress and viscosity), but no clear trends regarding the type of stabilization could be identified.

The slump flow of the SCCs plasticized with SP1 was measured 10 and 60 minutes after water addition. These SCCs exhibited a slump loss over time. The most marked slump loss was observed for the SCCs stabilized with the higher dosage of chemically stabilizers. This might be of importance when stabilized SCC needs to be transported over longer time.
The correlation between the different tested parameters was investigated. An important observation was the good correlation between the static yield stress and the thixotropy measured on matrix. These parameters result from two different approaches to test the structural build up. The good correlation indicates that they reflect a true material property.

### 4.3 Concrete compressive strength

It can be concluded that chemical stabilizers and superplasticizers can affect the compressive strength depending on the type and dosage of superplasticizer and stabilizer used, which is in agreement with the findings of (Khayat et al. 2010).
The filler additions improve the compressive strength of the tested SCCs after 7, 28 and 90 days. Limestone powder tends to increase the compressive strength of SCC more compared to other fillers. This effect has been attributed to the surface properties of limestone particles which function well as nucleation sites for the hydration products which accelerate the early cement hydration (Ye et al. 2005). However, this would probably not affect the 28 days strength much. Another explanation has been that the wide particle size distribution of limestone powder might improve the particle packing and hence increase the density of the matrix phase and the transition zones within cured concrete (Bosiljkov 2003). Besides these physical effects, chemical interaction between limestone powder and cement has been reported. The presence of limestone powder results in the formation of carboaluminate, thereby stabilizing the ettringite and reducing the porosity and possibly increasing the strength (De Weerdt et al. 2011).

# 5 Conclusion

The stabilizing effect of the measures tested depends strongly on the SP type used. Some of the high filler and chemical stabilizer dosages were able to stabilize the SCC plasticized with SP1, whereas hardly any of the measures tested tended to improve the stability of the SCC plasticized with SP2.

Chemical stabilizers mainly increase the static yield stress and the thixotropy of the matrix, reflecting an increase in structural build up. To maintain the slump flow a higher SP dosage is required. This does however not mean that the stabilizing effect of the chemical stabilizer is cancelled out by the increase SP dosage, but rather that a balance between the SP and chemical stabilizer dosage needs to be found. It should also be noted that in case of the SCC stabilized with SP1 a considerable slump loss can be observed between 10 and 60 minutes after water addition when using chemical stabilizers.

Adding filler to stabilize SCC, results generally in an increase in viscosity. However, the effect depends on the SP type used. In the case of SCCs plasticized with SP2, limestone filler also appears to increase the yield stress and thixotropy.

The combination of filler and chemical stabilizer affects the rheological properties by both increasing the viscosity and the yield stress of the matrix. However, combining filler and chemical stabilizer did not seem to improve the stability compared to using either one of them for the dosages tested.

It should be noted that a good correlation between the static yield stress and the thixotropy was observed. These parameters result from two different approaches to test the structural build up. The good correlation indicates that they reflect a true material property.

The effect of the stabilization methods on the compressive strength appears to depend on the SP type used. However, generally filler additions (incl. silica fume) improve the compressive strength after 7, 28 and 90 days. In the case SCCs with SP1, higher dosages of chemical stabilizers might result in a slight reduction in compressive strength.

# 6 Acknowledgements

The authors acknowledge the COncrete INnovation centre, COIN (http://www.coinweb.no) for facilitating this project.
We also want to express our thanks to the responsible of the concrete laboratory at SINTEF Building and Infrastructure, Knut Lervik, for conducting the laboratory work, assisting with the proportioning of the concretes and especially performing the Visual Segregation Index (VSI) classification.

# 7 References

Bosiljkov VB (2003) SCC mixes with poorly graded aggregate and high volume of limestone filler. Cement and Concrete Research 33 (9):1279-1286. doi:10.1016/s0008-8846(03)00013-9

De Schutter GM, Bartos PJ, Domone P, Gibbs J (2008) Self-compacting concrete. Whittles Publishing, Scotland, UK

De Weerdt K, Kjellsen KO, Sellevold EJ, Justnes H (2011) Synergy between fly ash and limestone powder in ternary cements. Cement and Concrete Composites 33 (1):30-38

Khayat KH, Hwang SD, Belaid K (2010) Performance of cast-in-place self-consolidating concrete made with various types of viscosity-enhancing admixtures. ACI Materials Journal 107 (4):403-412

Krieger IM, Dougherty TJ (1959) A mechanism for non-newtonian flow in suspensions of rigid spheres. Transactions of the Society of Rheology 3:137-152

Kristiansen B (2011) Experiences with SCC - challenges met in the field today. Paper presented at the Concrete Rheology Workshop, Trondheim, Norway,

Roussel N, Stefani C, Leroy R (2005) From mini-cone test to Abrams cone test: measurement of cement-based materials yield stress using slump tests. Cement and Concrete Research 35 (5):817-822. doi:10.1016/j.cemconres.2004.07.032

Vikan H (2005) Rheology and reactivity of cementitious binders with plasticizers. Doctoral thesis, NTNU Norwegian University of Science and Technology, Trondheim

Vikan H, De Weerdt K (2010) Stability of SCC - Chemical stabilizers versus filler. COIN Project report, vol 25. SINTEF, Trondheim

Wallevik JE (2009) Utvikling av stabilitetsmåler for SKB. Prosjektrapport for P653 "SKBB" DP 6. Norcem / ICI, Norway / Iceland

Ye G, Poppe A-M, De Schutter GM, van Breugel K, Liu X (2005) Microstructure of self-compacting concrete: experimental study and numerical simulation. Paper presented at the The 4th International RILEM Symposium on SCC, Chicago,

# A Appendices

## A.1 Sieve curves of the sand and aggregates used

**Table 6: The cumulative residue on the sieves given in mass %.**

| Sieve [mm] | Årdal 0/8 | Årdal 8/16 |
|---|---|---|
| 16 | - | 11.6 |
| 11.2 | - | 69.0 |
| 8 | 1.1 | 98.1 |
| 4 | 16.1 | 99.0 |
| 2 | 31.2 | 100 |
| 1 | 48.8 | 100 |
| 0.5 | 68.9 | 100 |
| 0.25 | 85.6 | 100 |
| 0.125 | 94.0 | 100 |
| 0.063 | 97.7 | 100 |

## A.2 Results for concrete

| | matrix | SP | Air (%) | | SU [mm] | | T500 [s] | | G [A] | | H [A.s] | | VSI | | | | segregated portion [%] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (l/m3) | (%) | 10 min | 60 min | 10 min | 60 min | 10 min | 60 min | 10 min | 60 min | 10 min | 60 min | 10 mix | 10 board | 60 mix | 60 board | 10 min | 60 min |
| SP1 | | | | | | | | | | | | | | | | | | |
| REF1 | 325 | 0.86 | 1 | 1 | 675 | 650 | 1.2 | 1.8 | 0.6 | 0.5 | 3.0 | 3.39 | 0.75 | 0.55 | 0.85 | 0.8 | | |
| REF2 | 325 | 0.68 | 0.5 | 0.8 | 675 | 635 | 1.1 | 1.8 | 0.5 | 0.3 | 3.1 | 6.9 | 0.9 | 0.7 | 0.6 | 0.5 | | |
| 0.4% S1 | 325 | 0.97 | 0.9 | 0.6 | 675 | 670 | 1.5 | 2.2 | 0.5 | 0.4 | 3.6 | 4.46 | 0.7 | 0.35 | 0.55 | 0.4 | | |
| 1.2% S1 | 325 | 1.07 | 1.1 | 1.4 | 660 | 615 | 1.1 | 1.2 | 0.6 | 0.5 | 4.4 | 5.3 | 0.5 | 0.3 | 0.4 | 0.3 | 9.3 | 8.8 |
| 1% S2 | 325 | 1.00 | 0.7 | 0.7 | 685 | 660 | 1.4 | 1.8 | 0.4 | 0.5 | 4.0 | 3.60 | 0.55 | 0.8 | 0.5 | 0.35 | | |
| 2% S2 | 325 | 1.00 | 0.9 | 1.2 | 695 | 637 | 1.0 | 3.2 | 0.5 | 0.8 | 4.5 | 5.5 | 0.9 | 0.6 | 0.6 | 0.6 | 18.7 | 10.9 |
| 12%LS | 338 | 0.67 | 1.2 | 2.1 | 675 | 635 | 1.2 | 1.8 | 0.4 | 0.6 | 4.5 | 4.30 | 0.5 | 0.2 | 0.45 | 0.15 | | |
| 24%LS | 352 | 0.83 | 1.4 | 1.5 | 668 | 665 | 1.9 | 2.4 | 0.3 | 0.3 | 5.0 | 4.67 | 0.5 | 0.3 | 0.5 | 0.15 | | |
| 12%W | 338 | 0.79 | 1.1 | 1.5 | 690 | 655 | 1.3 | 2.0 | 0.4 | 0.4 | 3.5 | 4.13 | 0.5 | 0.4 | 0.45 | 0.25 | | |
| 24%W | 352 | 0.90 | 0.9 | 0.6 | 687 | 690 | 1.9 | 2.0 | 0.3 | 0.1 | 4.7 | 6.59 | 0.5 | 0.3 | 0.5 | 0.3 | | |
| 12%C | 338 | 0.77 | 0.7 | 1.2 | 680 | 680 | 1.4 | 1.6 | 0.2 | 0.5 | 4.4 | 4.14 | 0.7 | 0.55 | 0.55 | 0.4 | | |
| 24%C | 352 | 0.94 | 1 | 0.6 | 695 | 665 | 2.0 | 1.8 | 0.5 | 0.1 | 6.1 | 6.29 | 0.7 | 0.35 | 0.65 | 0.3 | | |
| 0.4% S1 + 4%SF | | 1.20 | 0.6 | 0.7 | 678 | 660 | 1.8 | 2.2 | 0.4 | 0.4 | 5.5 | 6.4 | 0.7 | 0.4 | 0.5 | 0.4 | 15.7 | 11.7 |
| 1% S2 + 4%SF | | 1.20 | 0.5 | 0.6 | 660 | 660 | 1.6 | 2.5 | 0.4 | 0.3 | 5.3 | 7.2 | 0.7 | 0.4 | 0.6 | 0.4 | 14.0 | 11.6 |
| 0.4% S1 + 12%W | 338 | 0.94 | 1.4 | 1.2 | 675 | 638 | 1.3 | 1.9 | 0.4 | 0.4 | 4.9 | 6.6 | 0.7 | - | 0.6 | 0.4 | 8.7 | 3.8 |
| 1% S2 + 12%W | 338 | 1.30 | 0.9 | 0.9 | 697 | 665 | 1.4 | 2.7 | 0.2 | 0.1 | 9.2 | 11.0 | 0.8 | 0.7 | 0.7 | 0.6 | 20.3 | 15.2 |
| 0.4% S1 + 12%LS | 338 | 0.93 | 1.3 | 1.4 | 680 | 663 | 1.4 | 2.1 | 0.6 | 0.2 | 5.5 | 6.5 | 0.6 | 0.5 | 0.5 | 0.3 | 8.4 | 9.6 |
| 1% S2 + 24%LS | 338 | 0.97 | 0.9 | 0.8 | 690 | 665 | 1.4 | 2.6 | 0.3 | 0.3 | 5.4 | 5.5 | 0.7 | 0.4 | 0.7 | 0.4 | 15.9 | 12.9 |
| SP2 | | | | | | | | | | | | | | | | | | |
| REF | | 0.53 | | | 655 | | 1.2 | | 0.8 | | 3.4 | | 0.75 | 0.3 | | | | |
| 0.4% S1 | | 0.66 | | | 670 | | 1.3 | | 0.5 | | 3.6 | | 0.75 | 0.25 | | | | |
| 1.2% S1 | 325 | 1.16 | 0.7 | | 665 | | 1.4 | | 0.3 | | 3.9 | | 0.5 | 0.35 | | | 16.3 | |
| 1% S2 | | 0.71 | | | 680 | | 1.3 | | 0.6 | | 3.2 | | 0.7 | 0.4 | | | | |
| 2% S2 | 325 | 0.92 | 1 | | 670 | | 1.4 | | 0.3 | | 5.5 | | 0.85 | 0.65 | | | 14.6 | |
| 24%LS | | 0.60 | | | 670 | | 1.6 | | 0.4 | | 4.4 | | 0.8 | 0.4 | | | | |
| 24%W | | 0.78 | | | 710 | | 1.8 | | 0.3 | | 5.0 | | 0.8 | 0.4 | | | | |
| 24%C | | 0.72 | | | 700 | | 2.2 | | 0.4 | | 5.0 | | 0.75 | 0.35 | | | | |
| 0.4% S1 + 4%SF | | 0.83 | 1.1 | | 665 | | 1.7 | | 0.5 | | 7.6 | | 0.7 | 0.4 | | | 4.0 | |
| 1% S2 + 4%SF | | 0.89 | 1.1 | | 675 | | 1.8 | | 0.6 | | 6.8 | | 0.75 | 0.45 | | | 13.1 | |
| 0.4% S1 + 12%W | 338 | 0.97 | 0.7 | | 690 | | 1.5 | | 0.0 | | 6.9 | | 0.9 | 0.7 | | | 22.6 | |
| 1% S2 + 12%W | 338 | 0.82 | 0.9 | | 685 | | 1.5 | | 0.4 | | 5.4 | | 0.75 | 0.5 | | | 9.4 | |
| 0.4% S1 + 12%LS | 338 | 0.86 | 0.7 | | 685 | | 1.7 | | 0.0 | | 10.7 | | 0.75 | 0.6 | | | 24.6 | |
| 1% S2 + 24%LS | 338 | 0.87 | 0.9 | | 700 | | 1.7 | | 0.1 | | 8.5 | | 0.75 | 0.55 | | | 18.6 | |

## A.3 Results for paste

## Rheological properties of stabilized SCC – using fillers, admixtures or a combination

| | SP | $\tau_0$ | μ | thixotropy | gel strength. | static yield stress |
|---|---|---|---|---|---|---|
| | [%] | [Pa] | [Pa.s] | [Pa.s] | [Pa] | [Pa] |
| SP1 | | | | | | |
| REF1 | 0.86 | 0.4 | 0.06 | 3.1 | 1.2 | 0.26 |
| REF2 | 0.68 | -0.6 | 0.33 | 9.9 | 1.5 | 0.98 |
| 0.4%S1 | 0.97 | 4.7 | 0.19 | 20.7 | 2.2 | 0.64 |
| 1.2%S1 | 1.07 | 1.3 | 0.27 | 21.5 | 2.2 | 2.28 |
| 1%S2 | 1.00 | 1.4 | 0.24 | 15.7 | 3.4 | 0.61 |
| 2%S2 | 1.00 | 3.1 | 0.32 | 24.0 | 4.3 | 2.56 |
| 12%LS | 0.67 | 0.5 | 0.23 | 8.7 | 1.5 | 0.35 |
| 24%LS | 0.83 | -2.2 | 0.46 | 6.0 | 1.8 | 0.56 |
| 12%W | 0.79 | 0.8 | 0.25 | 7.8 | 1.5 | 0.23 |
| 24%W | 0.90 | -1.0 | 0.41 | 3.4 | 1.2 | 0.15 |
| 12%C | 0.77 | 0.4 | 0.34 | 12.0 | 2.2 | 0.53 |
| 24%C | 0.94 | -1.5 | 0.46 | 5.1 | 1.8 | 0.28 |
| 0.4%S1 + 4%SF | 1.20 | 1.0 | 0.37 | 19.6 | 3.4 | 1.70 |
| 1%S2 + 4%SF | 1.20 | -0.4 | 0.45 | 22.1 | 5.3 | 2.27 |
| 0.4%S1 + 12%W | 0.94 | 1.5 | 0.38 | 21.6 | 3.4 | 1.71 |
| 1%S2 + 12%W | 1.30 | 2.6 | 0.34 | 25.8 | 8.1 | 1.86 |
| 0.4%S1 + 12%LS | 0.93 | 0.0 | 0.30 | 9.8 | 1.8 | 1.01 |
| 1%S2 + 12%LS | 0.97 | -0.7 | 0.32 | 11.2 | 2.2 | 1.44 |
| SP2 | | | | | | |
| REF | 0.53 | 0.4 | 0.14 | 3.7 | <0,5 | 0.24 |
| REF | | | | | | |
| 0.4%S1 | 0.66 | 2.1 | 0.24 | 15.7 | 1.6 | 0.70 |
| 1.2%S1 | 0.71 | 0.2 | 0.05 | 1.3 | <0,5 | 0.04 |
| 1%S2 | 1.16 | -1.9 | 0.24 | 2.0 | 0.5 | 0.20 |
| 2%S2 | 0.92 | -1.0 | 0.37 | 8.1 | 1.8 | 1.10 |
| 12%LS | | | | | | |
| 24%LS | 0.60 | 0.4 | 0.63 | 23.3 | 3.9 | 3.10 |
| 12%W | | | | | | |
| 24%W | 0.78 | -4.1 | 0.58 | 0.1 | <0,5 | 0.07 |
| 12%C | | | | | | |
| 24%C | 0.72 | -1.3 | 0.47 | 5.5 | 1.5 | 0.77 |
| 0.4%S1 + 4%SF | 0.83 | -2.8 | 0.37 | 3.3 | 1.0 | 0.22 |
| 1%S2 + 4%SF | 0.89 | -3.1 | 0.36 | 3.5 | 1.2 | 0.38 |
| 0.4%S1 + 12%W | 0.97 | -3.4 | 0.41 | 1.6 | 0.6 | 0.09 |
| 1%S2 + 12%W | 0.82 | -2.8 | 0.32 | 1.8 | 0.8 | 0.22 |
| 0.4%S1 + 12%LS | 0.86 | -1.4 | 0.34 | 5.8 | 1.5 | 0.55 |
| 1%S2 + 12%LS | 0.87 | -0.8 | 0.36 | 11.2 | 2.2 | 1.25 |

| | SP | $\tau_0$ | μ | thixotropy | gel strength. | static yield stress |
|---|---|---|---|---|---|---|
| | [%] | [Pa] | [Pa.s] | [Pa.s] | [Pa] | [Pa] |
| SP1 | | | | | | |
| REF1 | 0.80 | 1.0 | 0.17 | 6.1 | 1.5 | 0.30 |
| REF2 | 0.80 | -2.2 | 0.29 | 3.9 | 0.8 | 0.45 |
| 0.4%S1 | 0.80 | 6.8 | 0.24 | 19.1 | 4.3 | 1.76 |
| 1.2%S1 | 0.80 | 1.2 | 0.26 | 21.1 | 2.2 | 2.29 |
| 1%S2 | 0.80 | 1.7 | 0.18 | 17.2 | 5.3 | 2.40 |
| 2%S2 | 0.80 | 5.1 | 0.36 | 33.2 | 5.3 | 3.72 |
| 12%LS | 0.80 | -0.2 | 0.31 | 4.2 | 1.2 | 0.32 |
| 24%LS | 0.80 | -2.1 | 0.41 | 6.5 | 1.8 | 0.68 |
| 12%W | 0.80 | 0.0 | 0.25 | 2.9 | 1.0 | 0.17 |
| 24%W | 0.80 | 0.7 | 0.43 | 13.7 | 3.4 | 0.79 |
| 12%C | 0.80 | 0.6 | 0.29 | 7.1 | 1.8 | 0.40 |
| 24%C | 0.80 | -1.0 | 0.45 | 7.4 | 2.2 | 0.62 |
| 0.4%S1 + 4%SF | 0.80 | 2.0 | 0.51 | 24.8 | 3.4 | 1.93 |
| 1%S2 + 4%SF | 0.80 | 3.5 | 0.48 | 35.4 | 6.5 | 3.88 |
| 0.4%S1 + 12%W | 0.80 | 7.6 | 0.47 | 39.3 | 6.5 | 2.82 |
| 1%S2 + 12%W | 0.80 | 4.7 | 0.45 | 46.3 | 12.4 | 4.70 |
| 0.4%S1 + 12%LS | 0.80 | 4.0 | 0.44 | 28.6 | 4.3 | 2.40 |
| 1%S2 + 12%LS | 0.80 | 3.2 | 0.44 | 35.2 | 5.3 | 4.18 |
| SP2 | | | | | | |
| REF | 0.70 | -1.7 | 0.26 | 0.0 | 0.5 | 0.02 |
| REF | 0.70 | -3.1 | 0.32 | 0.7 | 0.5 | 0.10 |
| 0.4%S1 | 0.70 | 0.9 | 0.33 | 1.8 | 0.8 | 0.57 |
| 1.2%S1 | 0.70 | 0.4 | 0.32 | 24.6 | 2.2 | 2.89 |
| 1%S2 | 0.70 | 0.2 | 0.19 | 1.9 | 0.8 | 0.08 |
| 2%S2 | 0.70 | 1.5 | 0.47 | 26.7 | 3.4 | 2.85 |
| 12%LS | 0.70 | -3.7 | 0.37 | 0.4 | 0.5 | 0.11 |
| 24%LS | 0.70 | -1.3 | 0.76 | 27.9 | 6.5 | 3.42 |
| 12%W | 0.70 | -1.6 | 0.27 | 0.1 | 0.5 | 0.02 |
| 24%W | 0.70 | -4.8 | 0.53 | 1.4 | 0.8 | 0.26 |
| 12%C | 0.70 | -3.5 | 0.37 | 1.1 | 0.6 | 0.16 |
| 24%C | 0.70 | -4.3 | 0.54 | 7.0 | 1.8 | 0.97 |
| 0.4%S1 + 4%SF | 0.70 | -1.7 | 0.46 | 11.0 | 1.8 | 0.93 |
| 1%S2 + 4%SF | 0.70 | -1.9 | 0.43 | 10.4 | 1.8 | 0.98 |
| 0.4%S1 + 12%W | 0.70 | -2.1 | 0.42 | 6.5 | 1.2 | 0.54 |
| 1%S2 + 12%W | 0.70 | -2.6 | 0.42 | 7.6 | 1.5 | 0.75 |
| 0.4%S1 + 12%LS | 0.70 | 0.8 | 0.48 | 19.4 | 2.8 | 1.66 |
| 1%S2 + 12%LS | 0.70 | 0.8 | 0.48 | 24.9 | 5.3 | 2.76 |

**SINTEF Building and Infrastructure** is the third largest building research institute in Europe. Our objective is to promote environmentally friendly, cost-effective products and solutions within the built environment. SINTEF Building and Infrastructure is Norway's leading provider of research-based knowledge to the construction sector. Through our activity in research and development, we have established a unique platform for disseminating knowledge throughout a large part of the construction industry.

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