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Effect of the mix design on the robustness of fresh self-compacting concrete

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A B S T R A C T

Self-compacting concrete (SCC) has many advantages compared to vibrated concrete. A disadvantage is the lower robustness of fresh SCC. SCC is more sensitive to small changes in the mix design, material properties, and the applied production methods. In an experimental program, the influence of important mix design parameters on the robustness of SCC was studied. First, the influence of the paste volume and the water-to-powder volumetric ratio was investigated. Depending on the mechanisms providing stability in the mixture, different levels of impact were observed. When the yield stress is the main factor providing stability in the mixture, a change in the water content will mainly affect the yield stress, making the stability of the yield stress the most important factor determining the robustness of the mixture and can be improved by lowering the paste volume. Analogue, the sensitivity of the plastic viscosity is determining the robustness of mixtures in which mainly the plastic viscosity is providing stability. The robustness of such a mixture can be improved by increasing the water-to-powder volumetric ratio. The influence of two types of viscosity modifying agents (VMA's) on the robustness of fresh SCC was examined in a second stage. The two used VMA's (diutan gum and attapulgite clay) were especially effective in SCC mixtures having a high yield stress and a low plastic viscosity. In mixtures having a low yield stress and a high plastic viscosity, the inclusion of a VMA in the mix design resulted in a decrease of the robustness.

1. Introduction

1.1. Self-compacting concrete

Self-compacting concrete (SCC) is a highly flowable type of concrete increasingly used in the precast concrete industry. Unlike ordinary vibrated concrete, SCC does not need any external compaction energy, eliminating possible problems caused by a poor external compaction [1]. Without the labor intensive, noisy and energy consuming vibration of fresh concrete, SCC proved to be very suitable for the precast industry and applications such as structures with dense reinforcements or complex formworks [1]. However, SCC is still not the first choice concrete for many applications: SCC is more sensitive to small variations in the mix proportions [2–4], material properties [5–9], or variations of the mixing method [10–15], and it is nowadays mainly used for casting situations with a thorough quality control.

Because of the more fluid behavior and therefore more complicated mix design of SCC, rheology – the study of the flow of matter – is often used to interpret experimental results. Most often, the Bingham model is used to describe the fluid behavior of fresh concrete. This model describes a linear relation between the shear stress τ and the shear rate $\dot{\gamma}$ using two parameters: the yield stress $\tau_{0,B}$ and the plastic viscosity μ_B (Eq. (1)). However, because non-linear behavior is often observed for SCC, the Modified Bingham model is also applicable for SCC. In this model (Eq. (2)), three

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parameters describe the rheological behavior: the yield stress $\tau_{0,MB}$, the Modified Bingham linear term μ_{MB}, and the Modified Bingham 2nd order coefficient c_{MB}.

$$\tau = \tau_{0,B} + \mu_B \cdot \dot{\gamma} \quad (1)$$

$$\tau = \tau_{0,MB} + \mu_{MB} \cdot \dot{\gamma} + c_{MB} \cdot \dot{\gamma}^2 \quad (2)$$

When designing a SCC mixture, the contradictory requirements of a high flowability and sufficient stability against segregation and bleeding can be met with multiple stability mechanisms. As shown in Fig. 1 (based on the rheograph from Wallevik and Wallevik [16]), well-performing SCC mixtures are situated in between two extremes: a relatively high yield stress and low plastic viscosity on the left side of the graph, and a zero or near-zero yield stress and high plastic viscosity on the right side of the graph. This variety of acceptable rheological parameters is necessary to meet the different workability requirements corresponding to different applications. Mixtures with a high yield stress and low plastic viscosity have a relatively small slump flow and low V-funnel flow time; mixtures with a low yield stress and high plastic viscosity have a larger slump flow and a high V-funnel flow time [17,18].

Dependent on whether yield stress or plastic viscosity provide stability, different mechanisms lead to an insufficient filling ability, passing ability, or stability of the mixture. When the yield stress should ensure the stability, the mixture can display segregation of the coarse aggregates or a lack of flowability (slump flow < 550 mm). SCC mixtures in which the plastic viscosity is providing stability could show excessive bleeding or become viscous and unworkable. SCC mixtures with intermediate characteristics can show a combination of several failure mechanisms.

- Lack of flowability versus segregation of coarse aggregates
  1) Lack of flowability: the mixture still meets most criteria for SCC (easy to process, self-consolidation, …), with the exception of sufficient flowability. A low slump flow (below 550 mm) and low L-box ratio (below 0.6) are inacceptable for most applications [19].
  2) Segregation of the coarse aggregates: due to segregation, the coarse aggregates of the mixtures are sinking. The Sieve Segregation Index (S.S.I.), an indicator of the segregation resistance of the mixture, is high.
- Highly viscous mixture, difficult to process versus excessive bleeding
  1) Highly viscous mixture: although a sufficiently large slump flow is obtained, the casting of the mixture is difficult or even impossible because of the highly viscous and very sticky behavior (V-funnel flow time > 25 s).
  2) Excessive bleeding: water migration can result in the formation of a water layer on the top surface of the fresh SCC [20,21].

1.2. The robustness of fresh SCC

The robustness of a concrete mixture is the capacity to retain its filling ability, passing ability, and segregation resistance despite small variations in the mix proportions, material properties, and the mixing method, which is a basic requirement for the production of concrete on a large scale. SCC in general has a lower robustness, due to the more complex mix design compared to vibrated concrete. The risk of segregation increases with decreasing yield stress and the risk of incompatibilities is increased by a higher number of constituents [22,23]. The delicate equilibrium between sufficient filling ability and adequate stability in terms of segregation and bleeding is the result of the use of superplasticizers and a higher powder content compared to conventional vibrated concrete. In some cases, a viscosity-modifying admixture (VMA) is also used to increase the stability of SCC [24,25].

The mechanisms governing the robustness of SCC have not been fully understood. Some approaches and guidelines have been developed to increase the robustness of SCC:

- Between the granular skeleton of the aggregates, a surplus of fines has to be available [3,26–28] preventing the coarse aggregate particles from dominating the rheology [28,29].
- Based on experiments in which cement was replaced by fly ash or silica fume, an increase of the paste volume is reported to increase the robustness [27,30,31].
- VMA's are often reported to increase the robustness of SCC [3,4,32–45]. The higher the water-to-powder ratio, the greater the possible increase in robustness using a VMA [35]. However, different VMA's have a different influence on the robustness of SCC [4,23,33,34,41,46,47]. In some cases, the use of VMA's even reduces the robustness of SCC [4,41].
- The influence of the water-to-powder ratio is unclear. Some researchers claim a higher water-to-powder ratio or the use of powders with a lower water demand result in a lower sensitivity to changes in the amount of free water [41]. Other studies report

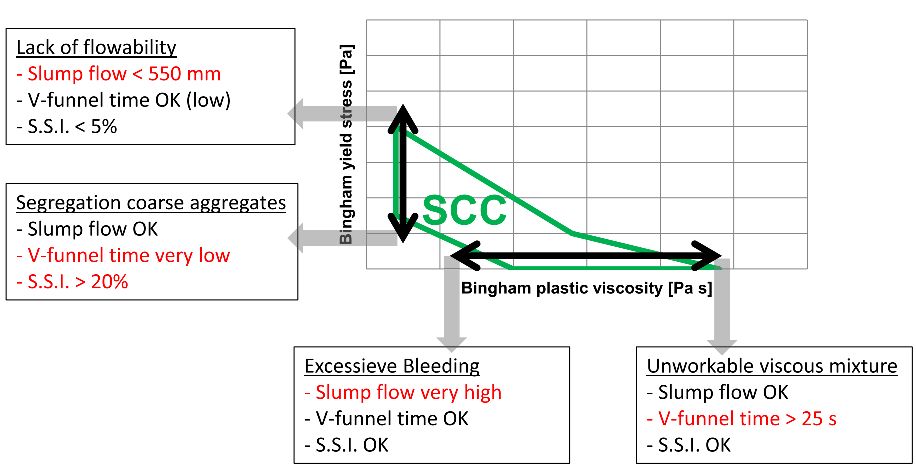

Fig. 1. Recommended SCC domain and failure modes in a Bingham rheograph.

a higher robustness of mixtures with a lower water-to-powder ratio and higher superplasticizer dosages [26].

- Some authors proposed a possible link between the thixotropy and robustness to explain the influence of the cement content or the inclusion of a VMA [22,48]. For clarification, more research in this area is needed.

1.3. Scope

The main goal of this investigation was to determine the combined effect of some of the listed approaches to enhance the robustness of SCC. The impact of the volumetric water-to-powder ratio and paste volume on the robustness of SCC is described in Section 3.1. Based on the experimental results, the impact of the mixture composition and use of a VMA on the robustness is discussed in Section 3.2. Rigueira et al. [2,49] showed that most problems are caused by variations of the water content, only the effect of small variations in the water content is considered in this experimental program. The EFNARC guidelines [19] recommend to ensure that a mix design is able to withstand changes of the water content up to 10 l/m^3, which corresponds to approximately 6% of the water content.

2. Experimental setup

2.1. Materials

Table 1 summarizes the materials used in both parts of the experimental program. The grading curves of all materials are summarized in Fig. 2, the chemical composition of the powders determined by XRF analysis is given in Table 2.

Attapulgite clay is often used as a suspending agent in pumpable concrete. During mixing, the flocculated clay breaks down into small needles with negative charges along its main axis and pH-dependent charges at the ends, strongly increasing the floc strength in cement pastes [50,51]. The increased flocculation rate caused by attapulgite clay results in a higher yield stress of the concrete. Diutan gum is a high molecular weight microbial polysaccharide, that fixes a part of the mixing water with hydrogen bonds when dissolved. The polymer chains intertwine at rest and align during shear flow [33,52,53].

2.2. Mix composition

Table 3 summarizes the mix compositions of nine reference mixtures used in Part 1. These mixtures vary in paste volume (350, 375, and 400 l/m^3) and volumetric water-to-powder ratio (0.75, 0.90, and 1.05) at a constant water-to-cement ratio. The powder content is defined as the content of fines, i.e. the cement and additions, excluding the sand and the paste fraction was defined as the combination of powder, water and admixtures in the mix

Table 2
Chemical composition of the cement and limestone filler.

	Cement Part 1 [%]	Cement Part 2 [%]	Limestone filler [%]
CaO	62.30	63.01	0.00
$CaCO_3$	0.00	0.00	98.8
SiO_2	18.77	18.55	0.11
Al_2O_3	6.00	5.83	0.04
Fe_2O_3	4.06	4.09	0.04
MgO	1.07	1.22	0.32
K_2O	0.58	0.60	0.00
Na_2O	0.51	0.53	0.01
SO_3	3.35	2.97	0.02
Cl^{2-}	0.067	0.086	<0.008
L.O.I	1.82	1.24	–
Insoluble residue	0.41	0.94	–

Table 1
Materials used during this experimental program.

Part 1: Influence of the water-to-powder ratio and paste volume	Part 2: Influence of VMA's
River gravel 2/8 and river gravel 8/16 with a density of respectively 2670 kg/m^3 and 2660 kg/m^3	
Limestone filler with a density of 2685 kg/m^3 and a specific surface area of 424 m^2/kg (calculated on using the particle size distribution given in Fig. 2).	
Polycarboxylate superplasticizer with a solid content of 35%.	
Rhine sand 0/5 with a density of 2630 kg/m^3.	Rhine sand 0/5 with a density of 2575 kg/m^3.
Portland cement CEM I 52.5 N with a density of 3126 kg/m^3 and a Blaine fineness of 370 m^2/kg.	Portland cement CEM I 52.5 N with a density of 3116 kg/m^3, and a Blaine fineness of 368 m^2/kg.
No VMA	Two types of VMA were applied: purified attapulgite clay and diutan gum.

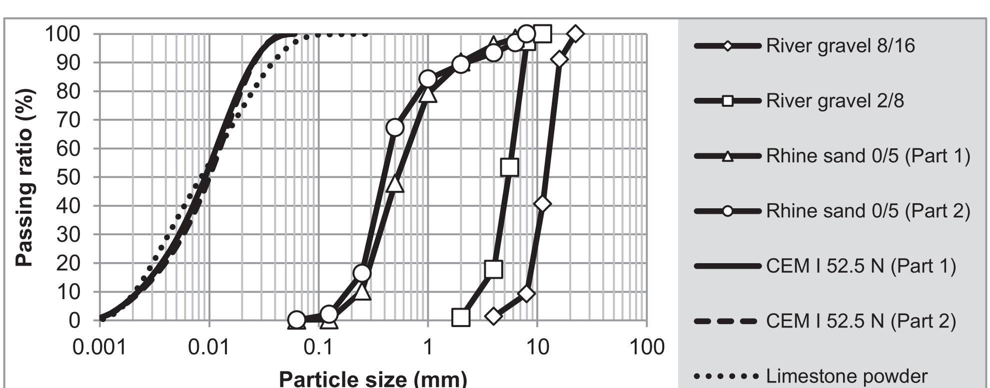

Fig. 2. The grading curve of all aggregates, cement, and limestone powder.

Table 3
Mix proportions of nine reference SCC mixtures used in Part 1 of the study.

Paste volume/water-to-powder ratio (by volume)	Sand 0/5	Gravel 2/8	Gravel 8/16	Cement I 52 N	Limestone filler	Water	SP dosage
[l/m³]/[−]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]	[l/m³]
400/0.75	800	279	459	312	346	171	3.31
400/0.90	800	279	459	344	269	189	2.50
400/1.05	800	279	459	373	204	205	1.95
375/0.75	835	291	478	292	324	161	3.95
375/0.90	835	291	478	323	252	178	2.80
375/1.05	835	291	478	349	191	192	2.00
350/0.75	869	303	498	273	302	150	5.31
350/0.90	869	303	498	301	236	166	3.63
350/1.05	869	303	498	326	178	179	2.38

composition. The different paste volumes and volumetric water-to-powder ratios in the reference mixtures correspond to the 20%, 50%, and 80% fractals of a database summarizing the properties of SCC mixtures of more than 175 scientific papers [54,55]. Only one water-to-cement ratio and a single type of binder was used in this experimental program. Investigating the impact of water-to-cement ratio and multiple binders would provide a more solid validation of the conclusions stated in this paper, but also double the experimental work. Due to the time constraints, these parameters were not included in the experimental program.

Different applications require different combinations of rheological characteristics of SCC. As a result, different slump flow values are obtained. The mixtures in this study have different rheological characteristics but always need to have a sufficient stability. Therefore, the superplasticizer dosage of each SCC was adjusted to keep the Sieve Stability Index (S.S.I.) in the range of 8–12%. For each of the mix compositions, the robustness was determined by variation of the water dosage of 8 l/m^3 water in excess or 8 l/m^3 less water compared to the reference concrete.

Two mixtures were considered in Part 2 of the experimental program representing two different approaches to obtain a stable SCC: one mixture was designed with a high yield stress and low plastic viscosity (Mix A), the other mixture had a low yield stress and a high plastic viscosity (Mix B). The composition of both mixtures is summarized in Table 4. A series for both reference mixtures consisted of three (Mix A) or four (Mix B) mixtures: one including 0.15% of cement weight of attapulgite clay, one including 0.05% of water weight of Diutan Gum (Mix B: two different superplasticizer dosages were tested), and one without VMA. The superplasticizer dosage was adjusted to reach the target rheology, meaning all conditions of SCC are met and still the same mechanism is providing the stability of the mixture: the yield stress in Mix A and the plastic viscosity in Mix B. The robustness of each mixture is determined by changing the water content with ±10 l/m^3. The change in the water content is slightly increased compared to Part 1 of the study, since more robustness was expected for mixtures containing a VMA.

Table 4
Mix proportions used in Part 2.

	Mix A	Mix B
River gravel 8/16 [kg/m³]	470	470
River gravel 2/8 [kg/m³]	266	265
Rhine sand 0/5 [kg/m³]	835	834
Limestone filler [kg/m³]	160	250
Cement [kg/m³]	390	350
Water [kg/m³]	195	175
Superplasticizer [l/m³]	1.86	4.00
Water-to-powder volumetric ratio [−]	1.05	0.85
Paste volume [l/m³]	380	380

2.3. Testing methods

The following mixing procedure was applied to prepare SCC in a planetary pan mixer having a capacity of 50 L:

- Mixing the aggregates, cement, and filler for 1 min.
- During another minute of mixing, the water is added.
- After addition of the superplasticizer, the concrete is mixed for two more minutes. In case a VMA was included in the mix composition, it was added 30 s after the addition of the superplasticizer.

Larger variations in the measured workability parameters (slump flow, V-funnel time, sieve stability, air content and density) relate to a lower robustness of the mixture. In order to determine variations of the rheological parameters, the robustness with regard to rheological characteristics was evaluated in Part 2 of this experimental program. The rheological characteristics were determined using an ICAR rheometer with a 6-bladed vane having a diameter of 127 mm and a height of 127 mm. A ribbed cylindrical bucket forming the outer cylinder had a diameter of 286 mm. The rotational velocity profile to measure the torque is given in Fig. 3. The data measured during the last two seconds of every rotational velocity step of the first stepwise decrease was used to calculate the Modified Bingham rheological parameters [56] (Eq. (2)). A second preshear step was executed and stepwise breakdown is included in the rotational velocity profile (Fig. 3) to verify whether segregation happened during the rheological test. When plug flow occurred, a plug flow correction was applied in the analysis [56].

In the analysis, the "*differential viscosity*" is selected for the discussion of the plastic viscosity results. This parameter is the first derivative of the shear stress to the shear rate at 5 s^{-1} (Eq. (3)) and

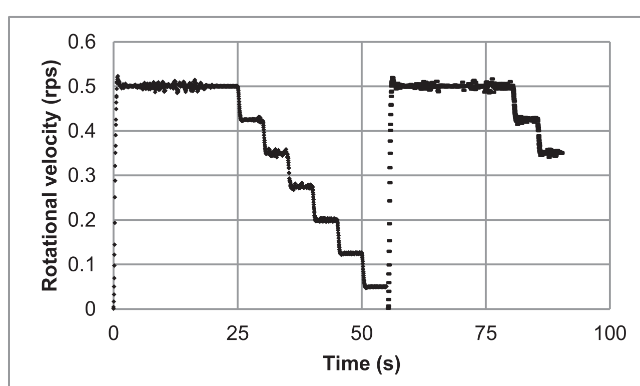

Fig. 3. The rotational velocity profile applied during the rheometer tests.

simplifies the discussion of the non-linear rheological data. A shear rate of 5 s^{-1} was chosen, but similar conclusions can be drawn based upon the first derivative of the shear stress at shear rates of 3 s^{-1} or 7 s^{-1}.

$$\eta_{5\ s^{-1}} = \mu_{MB} + 2 \cdot c_{MB} \cdot 5 \tag{3}$$

3. Experimental results

3.1. Part 1: influence of the water-to-powder ratio and paste volume

Figs. 4–7 and Tables 5 and 6 summarize the fresh properties of all mixtures of Part 1 of the study (9 reference mixtures and 18 adjusted mixtures) caused by variations induced by ± 8 l/m^3 of water: the change of the test response due to the presence of more or less water is expressed per liter water (e.g. The change in slump flow: ΔSF/16 l/m^3, see Equation (4)) and the ratio of the response interval (difference between the largest and the smallest test response) divided by the tests response of the reference mixture and the water variation (eg. ΔSF/SF$_{ref}$/16 l/m^3, Equation (5)). Both parameters reflect the slope of test response variation in Figs. 4–7, once in absolute terms and once relative to the reference value. Due to the limited availability of the concrete rheometer at the time of testing, only a restricted number of mixtures was subjected to a rheological test during Part 1 of the experimental program. Fig. 6d illustrates the rheological results of the mixtures of Part 1 of the experimental program for which the rheological parameters have been determined.

$$\frac{\Delta SF}{16\frac{l}{m^3}} = \frac{SF_{+8\ l/m^3} - SF_{-8\ l/m^3}}{+8\ l/m^3 - (-8\ l/m^3)} \tag{4}$$

$$\frac{\Delta SF}{SF_{ref} \cdot 16\ l/m^3} = \frac{SF_{+8l/m^3} - SF_{-8l/m^3}}{SF_{ref} \cdot (+8l/m^3 - (-8l/m^3))} \tag{5}$$

It is rare that excessive changes in the filling ability, passing ability, and segregation occur at the same time and cause a rejection of a mixture. Therefore, it is not considered useful to combine all three key characteristics into one global 'robustness value'. A better approach is to evaluate the robustness of a mixture by investigating its most critical parameter, which depends also on the application.

As shown in Figs. 4 and 6, the slump flow and S.S.I. become more sensitive to small variations in the water content with an increasing paste volume. The higher paste volume requires a lower dosage of superplasticizer to reach a S.S.I. of 10 ± 2% and as a result, in general a lower flowability is obtained (lower slump flow), making the mixture more sensitive to a small decrease in the water content, further decreasing the slump flow. The S.S.I. is also more affected by an increase in the water content when the paste volume increases (Table 5).

The robustness of the V-funnel time is mainly affected by the water-to-powder ratio (Fig. 5). The lower superplasticizer dosage of mixtures with a higher water-to-powder ratio, needed to reach a S.S.I. of 10 ± 2%, results in lower, more robust V-funnel times. Mixtures with a low water-to-powder ratio are more viscous and very sensitive to a small decrease in the water content. The risk of obtaining a very viscous, unworkable mixture can be reduced by increasing the paste volume, up to a limit at which the higher paste volume also negatively affects the robustness of the slump flow.

Table 6 summarizes the observed impact of the paste volume and water-to-powder ratio. The effect of the water-to-powder ratio on the robustness of the S.S.I. has been studied while varying both the water and powder contents in order to maintain the given paste volume. A different impact could have been obtained if the water or powder contents would have been kept constant.

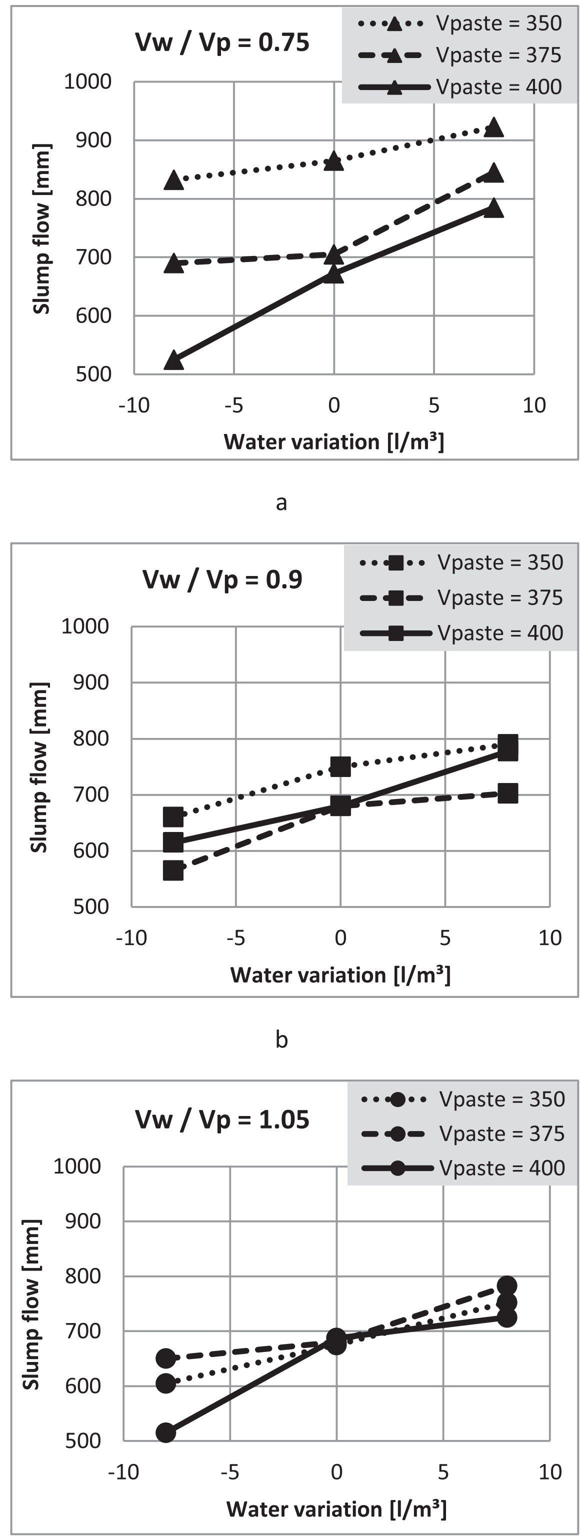

Fig. 4. Influence of the paste volume and water-to-powder rate on the slump flow.

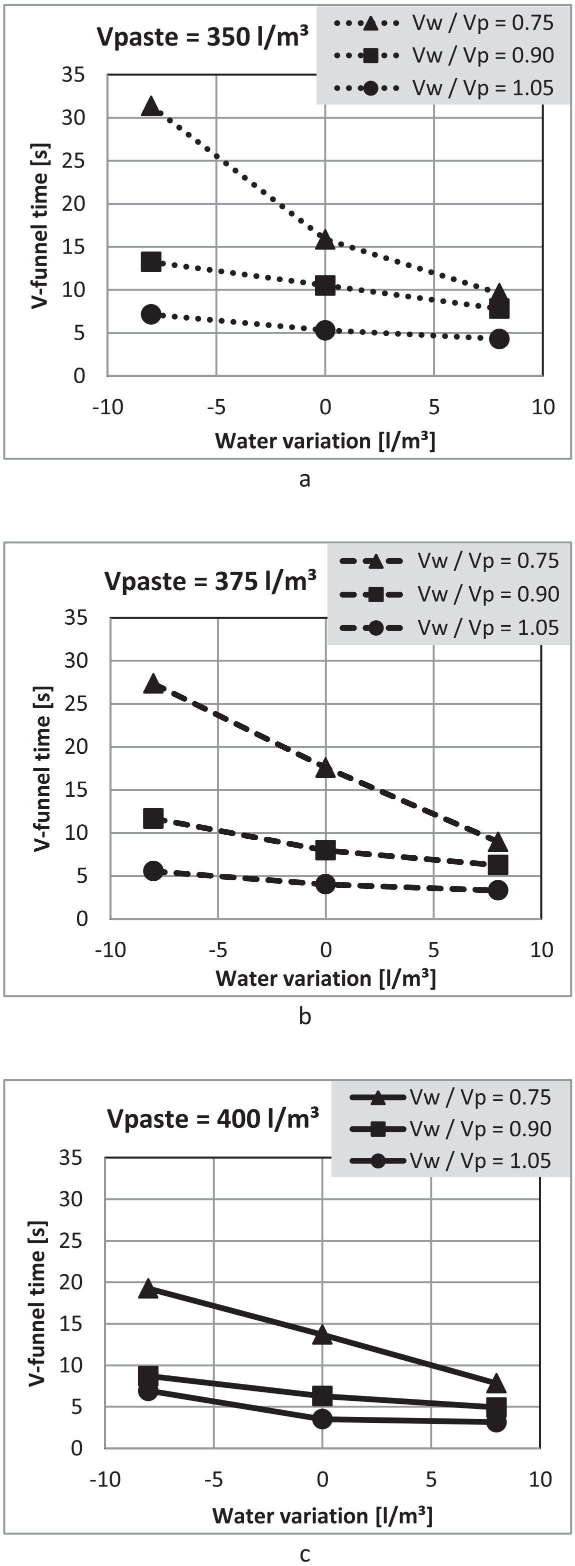

Fig. 5. Influence of the paste volume and water-to-powder rate on the V-funnel time.

3.2. Part 2: influence of VMA's

The influence of two VMA's on the robustness of two SCC mixtures was investigated in Part 2 of this study. A second goal of this part of the study was to determine whether the influence of a VMA on the robustness of a SCC with a high yield stress and low plastic viscosity (Mix A) is comparable with a SCC mixture having a low yield stress and high plastic viscosity (Mix B).

All test results are plotted in Figs. 8–11. An overview of the fresh properties and the robustness indicators of the mixtures are provided in Table 7. Two mixtures containing diutan gum were considered: one with a lower superplasticizer dosage which was very sensitive to a decrease of the water content, and one with a higher superplasticizer dosage which was very sensitive to an increase of the water content and suffered from bleeding.

Table 7 and Figs. 8–11 indicate that Mix A reacts differently to the inclusion of a VMA in the mix design than Mix B. The addition of VMA increased the robustness of the slump flow for Mix A and decreased the robustness of the slump flow for Mix B (Fig. 8). The V-funnel flow robustness was about the same for all mixtures, except Mix B containing diutan gum, which became very viscous when the water dosage was reduced by 10 l/m^3 (Fig. 9). When the same mixture was reproduced with a higher dosage of superplasticizer, a similar V-funnel robustness as the reference Mix B was observed. When a VMA is added, the S.S.I. of Mix A became more sensitive to an excess of water and less sensitive to a lack of water, resulting in a similar S.S.I. robustness as the reference Mix A (Fig. 10). Mix B, however, was much more sensitive to an excess of water. Although such high S.S.I. values are reported to be unacceptable, no pronounced bleeding and segregation was observed during the testing of these mixtures. Only Mix B with diutan gum and including a very high superplasticizer amount suffered from severe bleeding and segregation.

The rheological behavior of the SCC mixtures is characterized by two parameters in the rheograph illustrated in Fig. 11: the yield stress and the first derivative of the shear stress to the shear rate at a rotational speed of 5 s^{-1}. The addition of a VMA in Mix A with a high yield stress and low plastic viscosity resulted in a significant increase of the yield stress robustness, but had only little impact on the robustness of the plastic viscosity. In Mix B, having a small yield stress and a high plastic viscosity, both VMA's decreased the robustness of the yield stress and plastic viscosity. In order to reduce the pronounced effect of 10 l/m^3 less water, a Mix B including diutan gum and a higher dosage of superplasticizer was produced. This mixture, having a slump flow of 785 mm had an enhanced robustness of the rheological parameters, but suffered from severe bleeding and segregation.

4. Discussion

Plotting the test responses of mixtures of Part 1 with regard to slump flow and V-funnel time in a single diagram, as is illustrated in Fig. 12, robustness seems to be related to the mechanism providing stability in the mixture. In the following discussion, SCC mixtures having a high yield stress and low plastic viscosity will be referred to as 'A-SCC' and SCC mixtures with a low yield stress and high plastic viscosity will be referred to as 'B-SCC'.

The robustness of SCC mixtures with a smaller slump flow and a short V-funnel time (left side of the graph, A-SCC) is mainly determined by the robustness of the slump flow, and thus the yield stress. Mixtures with a larger slump flow and a high V-funnel time (right side of the graph, B-SCC) are balancing in between bleeding and excessive stickiness. Since the slump flow stays more or less stable, the robustness is mainly determined by the variations in V-Funnel flow time, and thus plastic viscosity, induced by the relative changes in the water content.

Based on the experimental results plotted in Fig. 12, the following conclusions can be drawn:

- For SCC mixtures having a high yield stress and low plastic viscosity (high water-to-powder ratio, small dose of

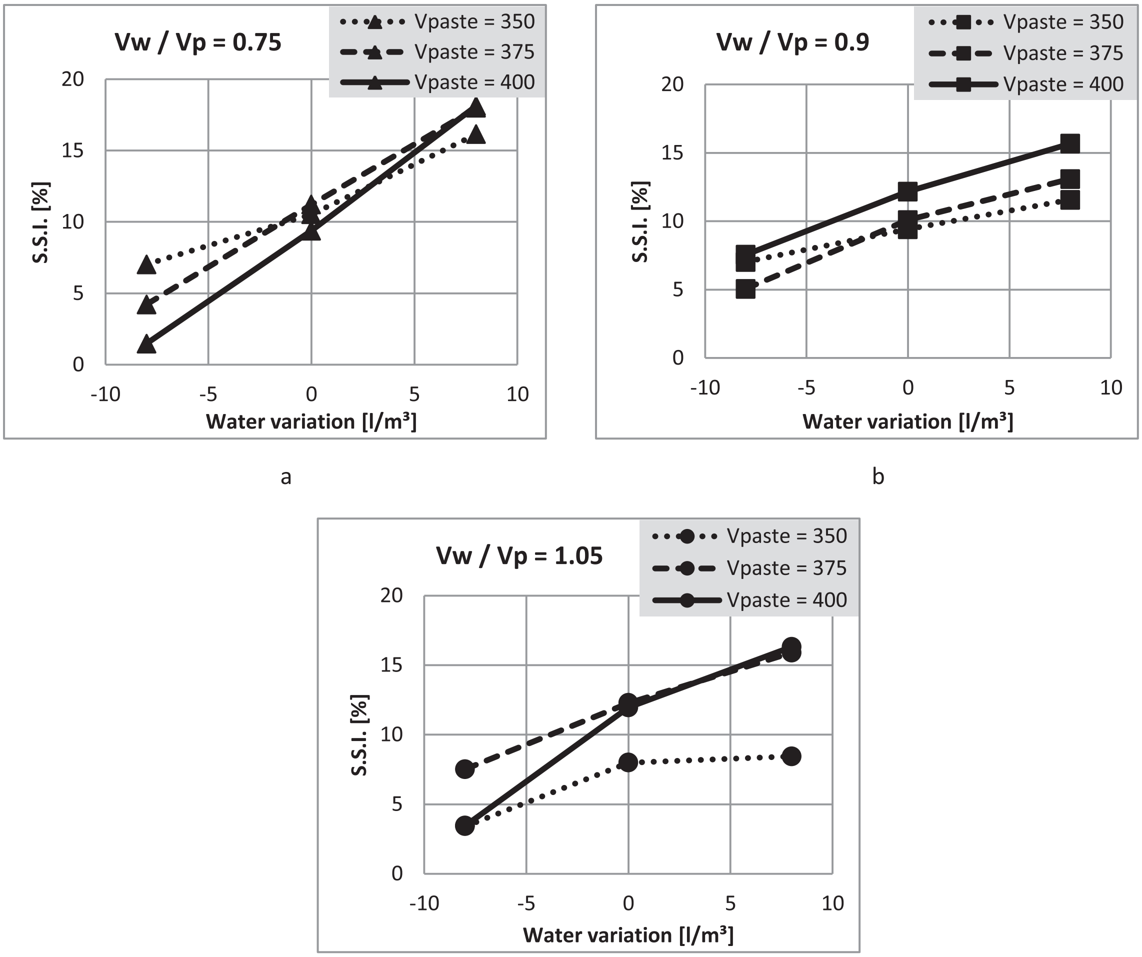

Fig. 6. Influence of the paste volume and water-to-powder rate on the sieve stability.

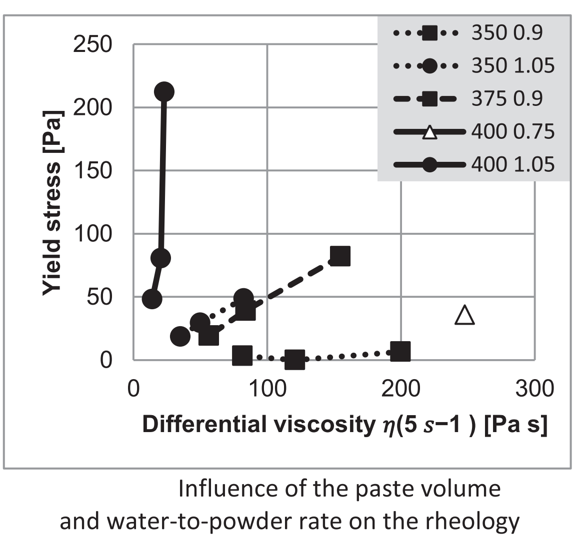

Fig. 7. Influence of the paste volume and water-to-powder rate on the rheology.

superplasticizer, A-SCC), a smaller volume of a less viscous paste has as a result a relatively higher robustness compared to a larger volume of highly flowable paste (B-SCC).

- For SCC mixtures with a low yield stress and high plastic viscosity (low water-to-powder ratio, larger dose of superplasticizer, B-SCC), a larger volume of less flowable paste results in a more robust mixture than a smaller volume of more flowable paste.

Although diutan gum and attapulgite clay have different mechanisms affecting robustness, both VMAs had a similar impact on the robustness: both VMAs increased the robustness of the A-SCC and reduced the robustness of B-SCC (Fig. 11). The positive impact of a VMA on A-SCC might be caused by fixing a part of the free water in these mixtures. Because these mixtures are less sensitive to bleeding, a moderate increase of the superplasticizer dosage does not cause any problems. Diutan gum increases the plastic viscosity and yield stress, providing more resistance to changes of the water content compared to attapulgite clay which only affects the yield stress of SCC.

In B-SCC mixtures, the addition of a VMA caused a decrease of the robustness. In these mixtures, a higher superplasticizer dosage is needed to compensate for the part of the water fixed by the VMA. As a result a more narrow area of acceptance in between an excessive bleeding and an unworkable viscous behavior is obtained, lowering the robustness against small variations in the water content. The preferred approach to enhance the robustness in B-SCC mixtures would be to decrease both the plastic viscosity and superplasticizer dosage. For example, in mixtures composed with a

Table 5
Workability test responses and robustness of nine reference SCC mixes caused by variations due to 8 l/m^3 more or less water.

Paste volume (l/m3)/water-powder ratio	400/0.75	400/0.90	400/1.05	375/0.75	375/0.90	375/1.05	350/0.75	350/0.90	350/1.05
Slump flow [mm]	**673**	**680**	**688**	**705**	**680**	**680**	**865**	**750**	**675**
ΔSF/16 l/m^3	16.3	10.2	13.1	9.7	8.6	8.3	5.6	8.1	9.2
ΔSF/SF$_{ref}$/16 l/m^3	0.024	0.015	0.019	0.014	0.013	0.012	0.006	0.011	0.014
V-funnel time [s]	**13.7**	**6.3**	**3.5**	**17.6**	**8.0**	**4.0**	**15.9**	**10.5**	**5.3**
ΔVF/16 l/m^3	0.71	0.24	0.24	1.15	0.34	0.14	1.36	0.34	0.18
ΔVF/VF$_{ref}$/16 l/m^3	0.052	0.038	0.067	0.065	0.043	0.035	0.086	0.032	0.033
S.S.I. [%]	**9.4**	**12.2**	**12.0**	**11.2**	**10.1**	**12.3**	**10.5**	**9.4**	**8.0**
ΔSSI/16 l/m^3	1.04	0.51	0.80	0.86	0.50	0.52	0.57	0.28	0.31
ΔSSI/SSI$_{ref}$/16 l/m^3	0.111	0.042	0.068	0.077	0.050	0.043	0.054	0.030	0.039
Density [kg/m^3]	**2475**	**2475**	**2475**	**2475**	**2475**	**2475**	**2475**	**2475**	**2475**
Air content [%]	**2.5**	**1.6**	**1.2**	**1.9**	**1.8**	**1.4**	**0.9**	**1.5**	**1.5**

Table 6
The influence of the paste volume and water-to-powder ratio on the robustness of SCC.

	Impact paste volume	Impact water-to-powder ratio
Slump flow	As the paste volume increases, the robustness of the slump flow to water variations decreases.	The water-to-powder ratio has no clear influence on the robustness of the slump flow.
V-funnel time	When the paste volume increases, the robustness slightly increases.	A lower water-to-powder ratio increases the sensitivity to small variations of the water content. Especially a small decrease of the water content can result in a very sticky, unworkable mixture.
S.S.I.	An increase of the paste volume results in a less robust S.S.I.	A decrease in water-to-powder volumetric ratio seems to decrease the robustness of the S.S.I., but the effect is less significant than a change in paste volume.

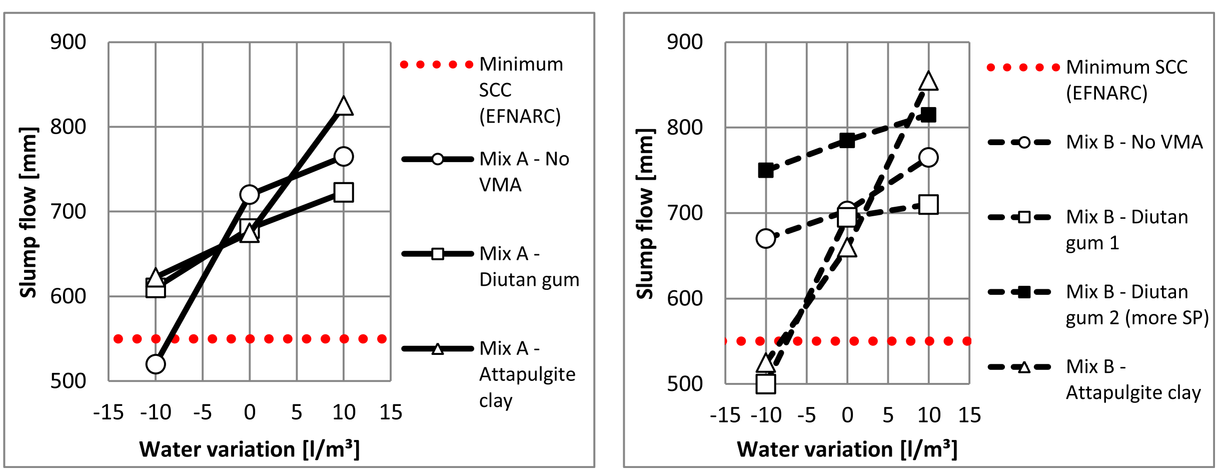

Fig. 8. The robustness of the slump flow test.

lower water-to-powder volume ratio and a higher paste volume, the dosage of superplasticizer can be reduced, resulting in a more stable paste (less susceptible to bleeding). A small variation in the water content of such mixtures has a smaller effect on the workability.

5. Recommendation for applications with SCC

Based on the experimental program described in this paper and the EFNARC guidelines on workability demands [19], recommendations are provided for mix design with optimum robustness dependent on the rheology (Table 8).

Composing SCC with a low plastic viscosity allows fast and convenient casting of large horizontal elements. A sufficiently high yield stress is necessary to provide stability to the SCC mixture. Robust SCC mixtures with such properties can be obtained by combining a high water-to-powder volume ratio with a low paste volume. The inclusion of diutan gum or attapulgite clay can further improve the robustness of such a mixture.

The stability of a slow, but far flowing mixture, i.e. a low yield stress SCC, is guaranteed by an intermediate plastic viscosity, which is obtained with a low water-to-powder ratio and relatively low paste volume in excess of filling the space of the granular skeleton between the aggregates. A maximum robustness can be reached by applying a sufficiently high but not too high water-to-powder ratio. Accordingly and for balanced characteristics, an intermediate water-to-powder ratio is recommended.

In order to prevent dynamic segregation during casting of long vertical elements, the concrete mixture needs to flow slowly and thus has a high plastic viscosity. Such behavior can be achieved by applying a low water-to-powder ratio. A low yield stress is necessary to ensure a proper filling of the space of the formwork and to flow around the reinforcement. The maximum robustness of such a mixture can be achieved with a higher paste volume, although it should not be too high, which makes the yield stress dominant and decreases the robustness with regard to flowability. Results of this

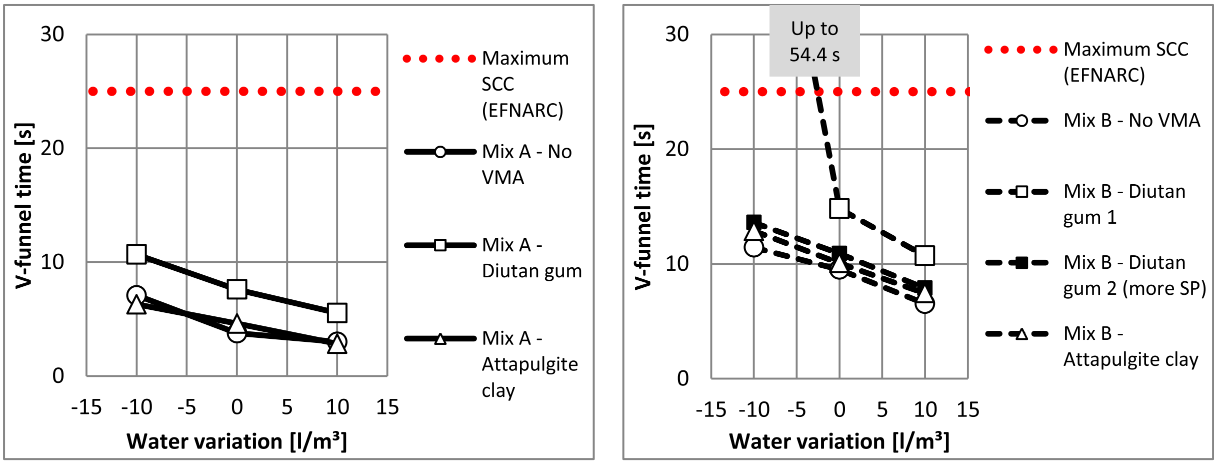

Fig. 9. The robustness of the V-funnel test.

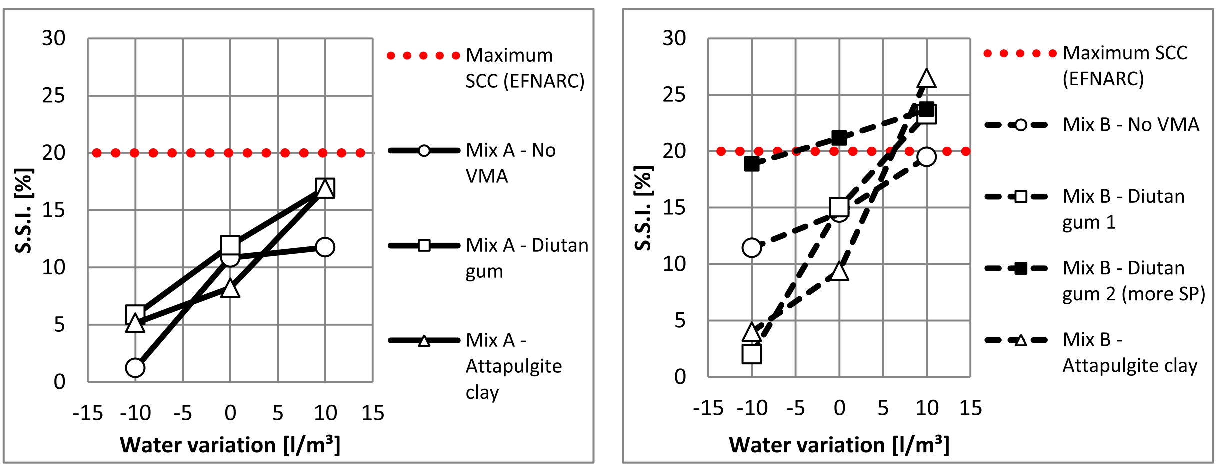

Fig. 10. The robustness of the S.S.I.

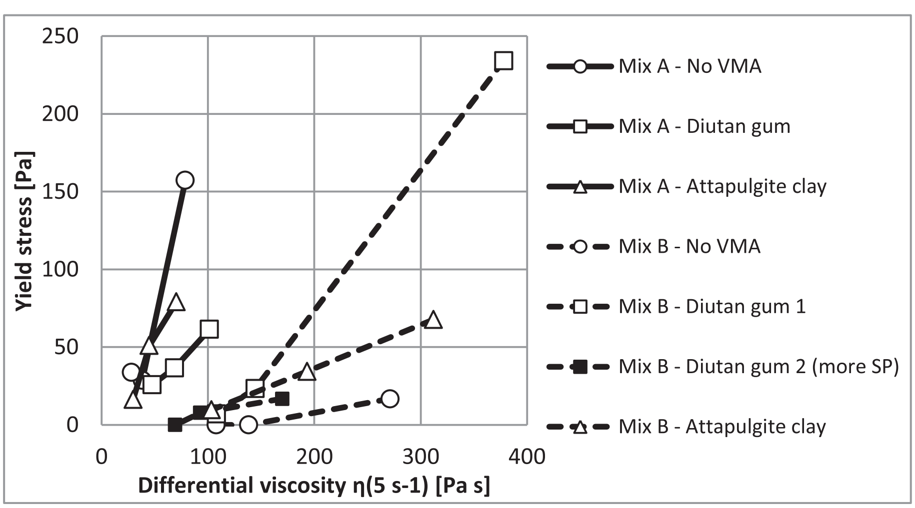

Fig. 11. Robustness of the rheological parameters. The "*differential viscosity*" is the derivative of the shear stress to the shear rate at 5 s^{-1} (Equation (3)).

experimental program indicated that the addition of a VMA decreased the robustness against changes in the water content.

In high vertical elements such as columns, the main requirements of SCC is sufficient stability provided by a high plastic viscosity. The yield stress should be low enough to allow completing the filling of the formwork and letting air bubbles

Table 7
The influence of VMA's on the sensitivity to changes in the water content. The "*differential viscosity*" is the first derivative of the shear stress to the shear rate at 5 s^{-1} (Equation (2)).

	Mix A No VMA	Mix A Diutan gum	Mix A Attapulgite clay	Mix B No VMA	Mix B Diutan gum 1	Mix B Diutan gum 2	Mix B Attapulgite clay
SP dosage [l/m^3]	1.86	3.29	2.00	4.00	6.57	8.00	3.14
Slump flow [mm]	**720**	**680**	**675**	**705**	**695**	**785**	**660**
ΔSF/20 l/m^3	12.3	5.6	10.1	4.8	10.5	3.3	16.5
ΔSF/SF$_{ref}$/20 l/m^3	0.017	0.008	0.015	0.007	0.015	0.004	0.025
V-funnel time [s]	**3.8**	**7.6**	**4.6**	**9.5**	**14.8**	**10.9**	**10.1**
ΔVF/20 l/m^3	0.2	0.26	0.17	0.25	2.19	0.29	0.27
ΔVF/VF$_{ref}$/20 l/m^3	0.054	0.034	0.038	0.026	0.148	0.026	0.027
S.S.I. [%]	**10.8**	**11.9**	**8.2**	**14.5**	**15**	**21.2**	**9.4**
ΔSSI/20 l/m^3	0.53	0.55	0.59	0.4	1.06	0.24	1.12
ΔSSI/SSI$_{ref}$/20 l/m^3	0.049	0.047	0.071	0.028	0.071	0.011	0.120
Yield stress [Pa]	**29**	**37**	**51**	**0**	**23**	**8**	**34**
ΔYS/20 l/m^3	6.2	1.8	3.1	0.8	11.4	0.8	2.9
ΔYS/YS$_{ref}$/20 l/m^3	0.212	0.049	0.062	–	0.485	0.109	0.084
Differential viscosity [Pa s]	**38**	**69**	**45**	**138**	**145**	**93**	**193**
ΔPV/20 l/m^3	2.5	2.7	2	8.2	13.5	5	10.4
ΔPV/PV$_{ref}$/20 l/m^3	0.066	0.039	0.045	0.059	0.093	0.054	0.054
Density [kg/m^3]	2350	2360	2350	2360	2370	2360	2370
Air content [%]	1.6	2	1.8	2	1.7	1.7	2.6
Modified Bingham parameters							
Yield stress $\tau_{0,MB}$ [Pa]	29	37	51	0	23	8	34
Modified Bingham linear term μ_{MB} [Pa s]	38	69	45	34	81	49	60
Modified Bingham 2nd order coefficient c_{MB} [Pa s^2]	0	0	0	10	6	4	13
Differential viscosity at 5 s-1 $\eta_{5s^{-1}}$ [Pa s]	**38**	**69**	**45**	**138**	**145**	**93**	**193**

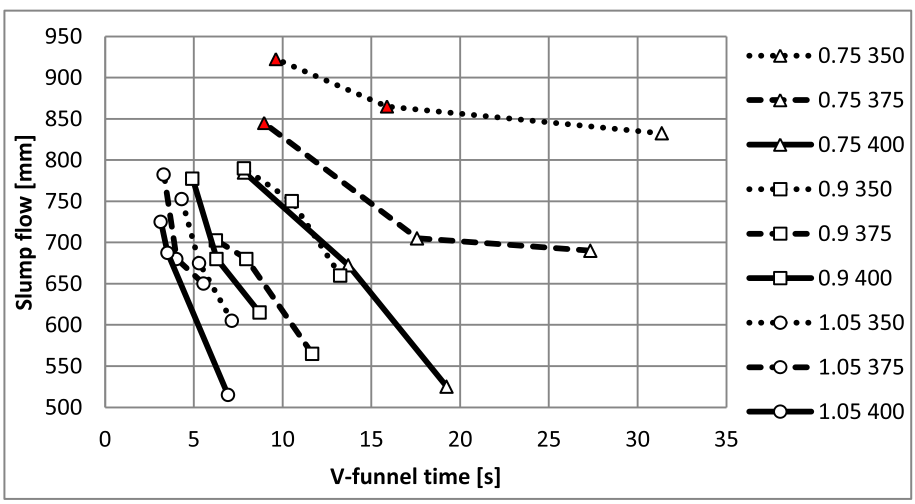

Fig. 12. The robustness of all mixtures illustrated in a workability box. Mixtures with severe bleeding are marked in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
The recommended mix design for a maximum robustness depends on the application.

Application	Recommended paste volume	Recommended volumetric water-to-powder ratio	Include a VMA?
Low plastic viscosity and high yield stress	Low	High	Yes
Low yield stress and intermediate plastic viscosity	Low	Intermediate	Yes
Low yield stress and a high plastic viscosity	Intermediate	Low	No
A zero yield stress and a high plastic viscosity	High	Low	No

escape the concrete. The most robust solution is a combination of a low water-to-powder ratio and a high paste volume. No VMA should be included in the mix design.

6. Conclusions

Because the lack of robustness is currently limiting the use of SCC, an experimental investigation was executed to determine the effect of different mix design parameters: the paste volume, the water-to-powder volumetric ratio, and the addition of VMA's (diutan gum and attapulgite clay). Dependent on the mechanism providing stability of the mixture, these mix design parameters can have a more or less pronounced impact on the robustness of SCC. The robustness of mixtures with a high yield stress and low plastic viscosity mainly depends on the robustness with regard to slump flow and Sieve Segregation Index (S.S.I.). In such mixtures, the yield stress mainly provides the stability and therefore determines the robustness of the mixture. The robustness can be improved by a decrease of the paste volume or including a VMA. Because the plastic viscosity is the mechanism providing stability in mixtures with a low yield stress and a high plastic viscosity, the robustness of the plastic viscosity mainly is determining the robustness of the mixture. It can be enhanced by increasing the water-to-powder volumetric ratio. The addition of a VMA does not improve robustness in this case. Future work will focus on the robustness on paste level, combined with a measurement of the structural buildup at rest.

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