The Combined Influence of Paste Volume and Volumetric Water-to-Powder Ratio on Robustness of Fresh Self-Compacting Concrete

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Abstract: In order to avoid durability problems caused by an inadequate consolidation of concrete, self-compacting concrete (SCC) has been developed. The mix design of SCC aims at balancing a minimum flowability allowing air bubbles to escape and a maximum flowability in order to avoid segregation. Because of the higher demands on mix design and additional requirements related to casting, SCC mixtures are in general more sensitive to small variations in its mix composition compared to conventional vibrated concrete. Besides improving the robustness of SCC with admixtures like Viscosity-Modifying Agents (VMAs), it is also important to find out why certain mixtures are more robust than others. This paper investigates the influence of the paste volume and the water-to-powder ratio (volumetric) on the robustness of fresh SCC mixtures. Nine SCC mixtures with a paste volume of 350, 375, and 400 l/m³ and a volumetric water-to-powder ratio of 0.75, 0.90, and 1.05 were subjected to a variation of ±8 l/m³ water. The robustness of the produced mixtures was quantified measuring the slump flow, V-funnel time, L-box ratio, and sieve stability.

Keywords: Robustness, Self-Compacting Concrete, Rheology, Paste Volume, Water-to-Powder ratio

1. Introduction

1.1. Self-compacting concrete

After investigating many durability problems of post-war Japanese concrete structures, Okamura and his team found that a majority of problems originated in a poor consolidation of concrete during the casting process. As a solution to avoid similar problems, a new type of concrete was developed for which external vibration was no longer needed to assure a good compactation: self-compacting concrete (SCC) [1, 2]. In order to combine sufficient fluidity – allowing air-bubbles to escape and complete formwork filling – and sufficient stability to avoid segregation, the high fluidity concrete contains higher powder content compared to conventional vibrated concrete, superplasticizer(s), and sometimes a viscosity-modifying admixture (VMA). However, because the target range for sufficient fluidity, sufficient segregation resistance, and to avoid an excessive stickiness is much smaller than the optimum range of conventional vibrated concrete, self-compacting mixtures are generally more sensitive to small variations in the mix proportions, materials properties, and casting circumstances.

To counter this larger sensitivity to small variations, also referred to as reduced robustness, a more severe quality control and better trained workers are needed. The use of SCC is nowadays still limited to cases where all conditions are well-controlled and situations in which an external compaction would cause great difficulties. To facilitate the use of SCC in general and especially for applications with specific requirements for fresh concrete, it is necessary to investigate the origin of the robustness of concrete.

1.2. The origin of the robustness

Although many parameters such as material characteristics [3-11], temperature [12-14], and shear history [15-18] affect the fresh behaviour of self-compacting concrete, most robustness studies focus on the influence of small changes in the material proportions [11, 19-42]. Of all changes in material proportions, inaccuracies in the water amount are responsible for the largest variations of the fresh behaviour of SCC [43, 44]. Therefore, many studies on the robustness of fresh SCC focus on the influence of small variations of the water content (± 5 to 10 l/m³). According to these publications, the sensitivity to small variations of the water content decreases as:

- A surplus of fine aggregates is included in the aggregates grading curve, preventing the coarse aggregates from becoming dominant [19-21, 45].
- The powder content increases [20, 21, 23].
- Part of the cement is substituted by silica fume or fly ash [22, 24].
- A VMA is added to the mixture [20, 28-39, 46].
- Certain types of superplasticizers are used [25-27].
- Opposing conclusions are drawn about the influence of the water-to-cement and water-to-powder ratio [19, 38]

The mechanisms and combination of influences of the powder content, the water-to-powder ratio, mineral additions and admixtures on the robustness are still unknown. Some authors indicate the importance of the paste volume, the paste density, and the paste viscosity [20, 21, 23], while others focus on the excess water in the concrete mix design [38] or make a link between the thixotropy and robustness [47, 48]. This paper attempts to determine the causes behind the influence of paste volume and volumetric water-to-powder ratio on the robustness of SCC.

2. Experimental work

2.1. Materials and mixing sequence

All mixtures are made with the same raw materials: Rhine sand 0/5, river gravel 2/8 and 8/16 (with a density of respectively 2630 kg/m³, 2670 kg/m³, and 2660 kg/m³), Portland cement CEM I 52.5 N (with a density of 3126 kg/m³ and a Blaine fineness of 370 m²/kg), limestone filler (with a density of 2685 kg/m³ and a specific surface area of 424 m²/kg, based on the particle size distribution), and a PCE superplasticiser with a solid content of 35%. The grading curve of the aggregates is illustrated in
Figure 1 and the chemical composition of the cement as determined by an XRF analysis is given in Table 1. After premixing the cement, filler, and dry aggregates for one minute in a planetary pan mixer, water was added to the mixer and mixing continued for another minute. Finally, the superplasticizer was added and the concrete was mixed for two more minutes.

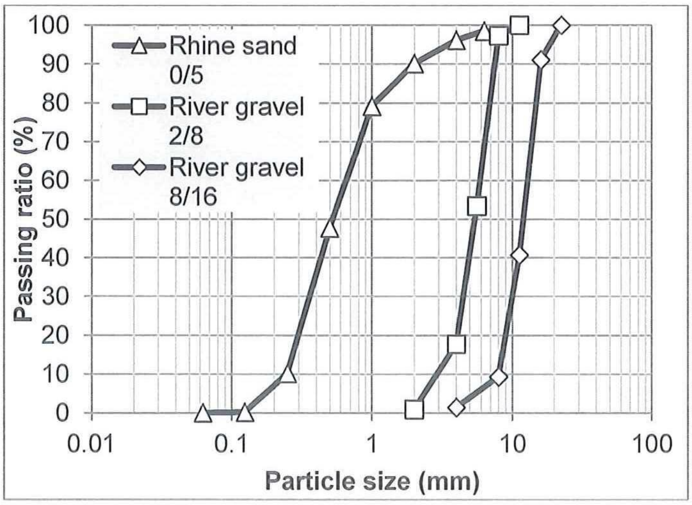

Figure 1. Grading curve of the aggregates

Table 1. Chemical composition of the cement

	Cement [%]
CaO	62.30
SiO_2	18.77
Al_2O_3	6.00
Fe_2O_3	4.06
MgO	1.07
K_2O	0.58
Na_2O	0.51
CO_2	0.60
SO_3	3.35
Cl^{2-}	0.067
L.O.I.	1.82
Insoluble rest	0.41

2.2. Mixture compositions

The robustness of nine SCC mixtures was determined by measuring the slump flow, V-funnel time, L-box ratio, sieve stability, air content and density of the mixtures subjected to a variation of ±8 l/m³ water. The mixtures, given in Table 2, have different paste volumes (350, 375, and 400 l/m³) and volumetric water-to-powder ratios (0.75, 0.90, and 1.05), keeping the water-to-cement ratio constant. These paste volumes and volumetric water-to-powder ratio's correspond with the 20%, 50%, and 80% fractals of a database summarizing the properties of SCC mixes used in more than 175 papers [49, 50]. The superplasticizer dosage was always determined such that the Sieve Stability Index (S.S.I., tested according to EN 12350-11) of the reference mixture is between 8 and 12%.

Table 2: Mix proportions of reference SCC mixes

Paste volume / water-to-powder ratio (by volume) [l/m³] / [-]	Sand 0/5 [kg/m³]	Gravel 2/8 [kg/m³]	Gravel 8/16 [kg/m³]	Cement I 52 N [kg/m³]	Limestone filler [kg/m³]	Water [kg/m³]	SP dosage [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

3. Experimental results

Table 3 and Table 4 summarize the fresh properties of the nine reference mixtures. In Table 4, for each workability test, the values for the reference mixtures are listed together with the change of the test response per liter water of the parameter (eg. ΔSF / 16 l/m³) and the ratio of the interval divided by the mean value (eg. $\Delta SF / SF_{ref}$). All workability tests except the L-box ratio gave a good picture of the impact of fluctuations of the water content on the fresh behaviour of the mixtures.

Table 3: Fresh state properties of nine reference SCC mixes

Paste volume / water-to-powder ratio [l/m³] / [-]	Slump flow [mm]	V-funnel time [s]	L-box ratio [-]	S.S.I. [%]	Density [kg/m³]	Air content [%]
400 / 0.75	673	13.7	0.82	9.4	2475	2.5
400 / 0.90	680	6.3	0.85	12.2	2369	1.6
400 / 1.05	688	3.5	0.83	12.0	2369	1.2
375 / 0.75	705	17.6	0.96	11.2	2394	1.9
375 / 0.90	680	8.0	0.91	10.1	2375	1.8
375 / 1.05	680	4.0	0.86	12.3	2372	1.4
350 / 0.75	865	15.9	1.00	10.5	2406	0.9
350 / 0.90	750	10.5	0.98	9.4	2375	1.5
350 / 1.05	675	5.3	0.80	8.0	2369	1.5

Table 4: The robustness of nine SCC mixes

	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	260	163	210	155	138	133	90	130	148
ΔSF / 16 l/m³	16.3	10.2	13.1	9.7	8.6	8.3	5.6	8.1	9.2
$\Delta SF / SF_{ref}$	0.39	0.24	0.31	0.22	0.20	0.19	0.10	0.17	0.22
V-funnel time [s]	**13.7**	**6.3**	**3.5**	**17.6**	**8.0**	**4.0**	**15.9**	**10.5**	**5.3**
ΔVF	11.4	3.8	3.8	18.4	5.4	2.2	21.8	5.4	2.8
ΔVF / 16 l/m³	0.71	0.24	0.24	1.15	0.34	0.14	1.36	0.34	0.18
$\Delta VF / VF_{ref}$	0.83	0.60	1.07	1.04	0.68	0.56	1.37	0.51	0.53
L-box ratio [-]	**0.82**	**0.85**	**0.83**	**0.96**	**0.91**	**0.86**	**1.00**	**0.98**	**0.8**
ΔLB	0.78	0.19	0.35	0.06	0.27	0.15	0.02	0.02	0.19
ΔLB / 16 l/m³	0.049	0.012	0.022	0.004	0.017	0.009	0.001	0.002	0.012
$\Delta LB / LB_{ref}$	0.95	0.22	0.41	0.06	0.29	0.17	0.02	0.02	0.23
S.S.I. [%]	**9.4**	**12.2**	**12.0**	**11.2**	**10.1**	**12.3**	**10.5**	**9.4**	**8.0**
ΔSSI	16.7	8.1	12.9	13.8	8.0	8.4	9.1	4.5	5.0
ΔSSI / 16 l/m³	1.04	0.51	0.80	0.86	0.50	0.52	0.57	0.28	0.31

$\Delta SSI / SSI_{ref}$	1.77	0.67	1.08	1.23	0.80	0.68	0.87	0.48	0.63

3.1. Variations of the slump flow

Because the superplasticizer dosage was always adjusted in order to have a S.S.I. of 10%±2%, the slump flow of the nine mixtures is not related to their paste volume or water-to-powder ratio (Table 3). However, as shown in Table 4 and Figure 2, the sensitivity of the slump flow to changes in the water content depends on the paste volume: the robustness of the flow decreases as the paste volume increases. Table 4 shows that the water-to-powder ratio of the mixtures has no clear influence on the robustness of the slump flow.

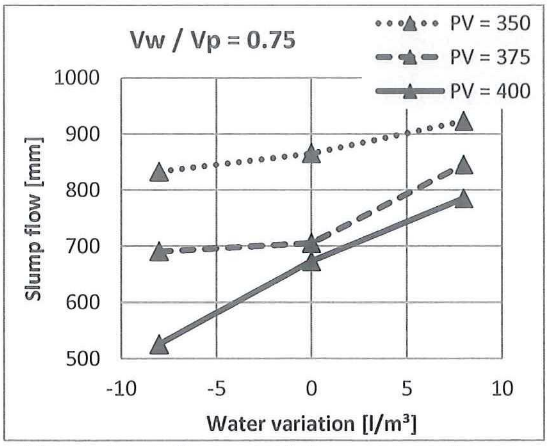

Figure 2a: Influence of the paste volume on the slump flow

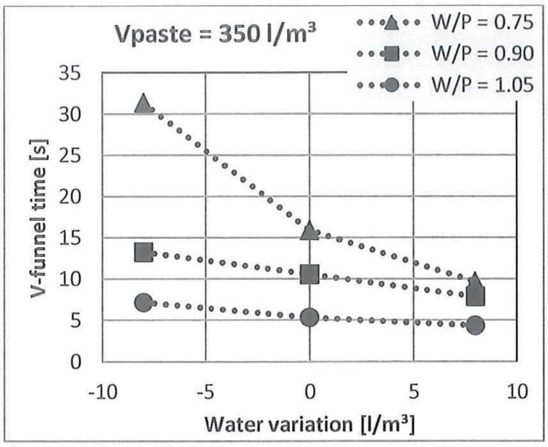

Figure 3a: Influence of the volumetric water-to-powder ratio on the V-funnel time

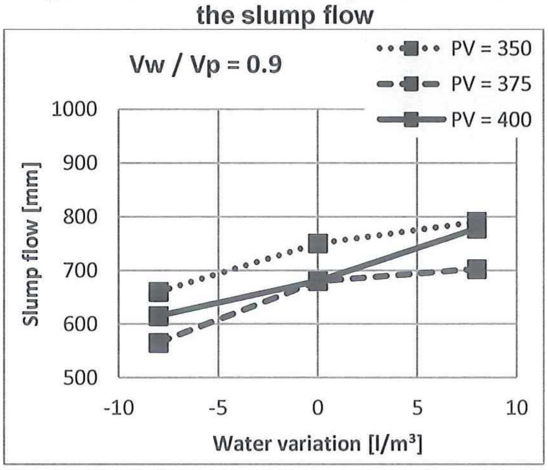

Figure 2b: Influence of the paste volume on the slump flow

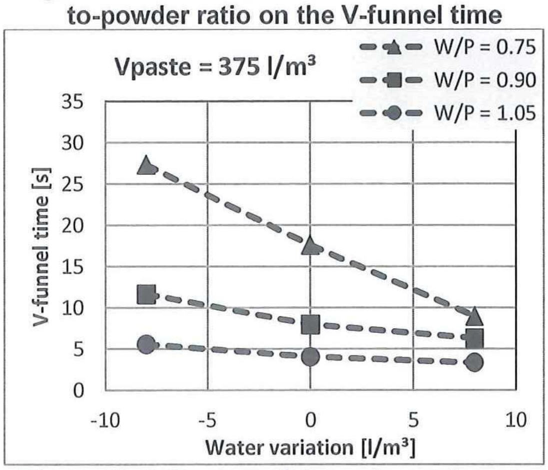

Figure 3b: Influence of the volumetric water-to-powder ratio on the V-funnel time

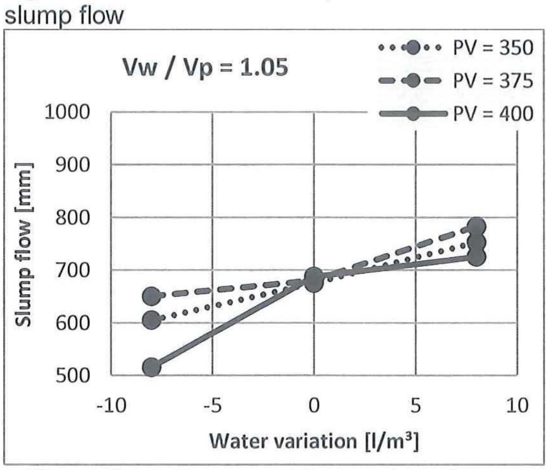

Figure 2c: Influence of the paste volume on

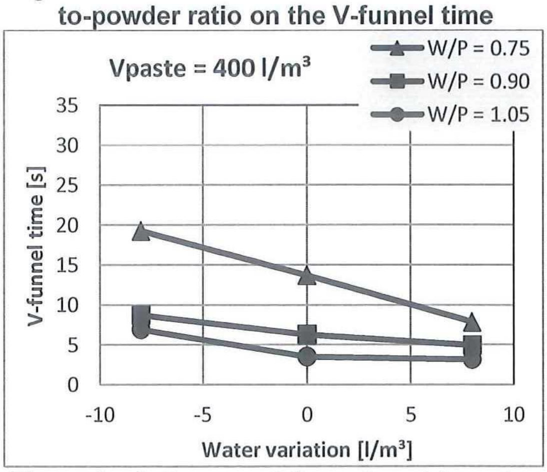

Figure 3c: Influence of the volumetric water-

the slump flow

to-powder ratio on the V-funnel time

3.2. *Variations of the V-funnel time*

When the paste volume increases, the V-funnel time of the mixtures decreases slightly (about 3 sec difference between 350 and 400 l/m³ for the same water-to-powder ratio); the sensitivity of the V-funnel time to variations in the water content also seems to be independent of the paste volume of the mixture. Mixtures with a higher water-to-powder ratio have a significant lower V-funnel time than mixtures with a lower water-to-powder ratio (see Tables 3 and 4). Especially, mixtures with a water-to-powder ratio of 0.75 are very sensitive to a decrease in the water content, making them very sticky and not easy to process. The robustness determined by changes in the V-funnel time therefore increases when the water-to-powder ratio increases (Figure 3).

3.3. *Variations of the L-box ratio*

Table 4 reveals no clear influence of the test responses on the L-box ratio results. The results are also difficult to interpret because of the poor flowability of the mixtures with 8 l/m³ less water, a paste volume of 400 l/m³ and volumetric water-to-powder ratios of 0.75 and 1.00, which have a slump flow of respectively 525 and 515 mm.

3.4. *Variations of the sieve stability*

As shown in Table 4 and Figure 4, an increase in the paste volume increases the sensitivity of the S.S.I. to variations in the water content. The paste volume has a larger effect than changes in the water-to-powder ratio.

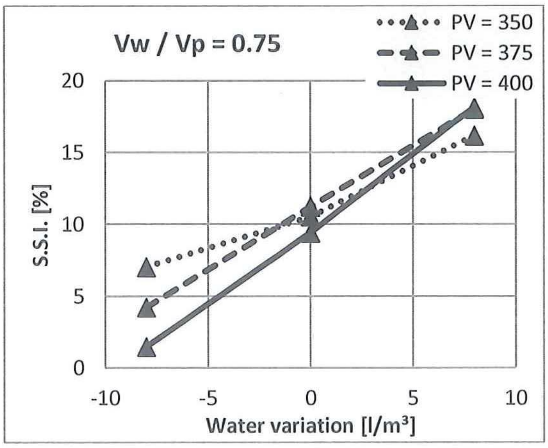

Figure 4a: Influence of the paste volume on the sieve stability

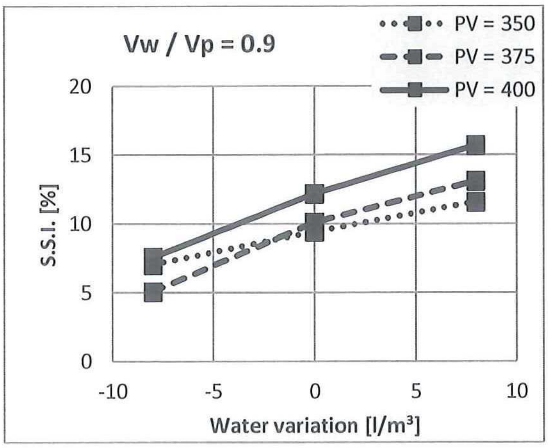

Figure 4b: Influence of the paste volume on the sieve stability

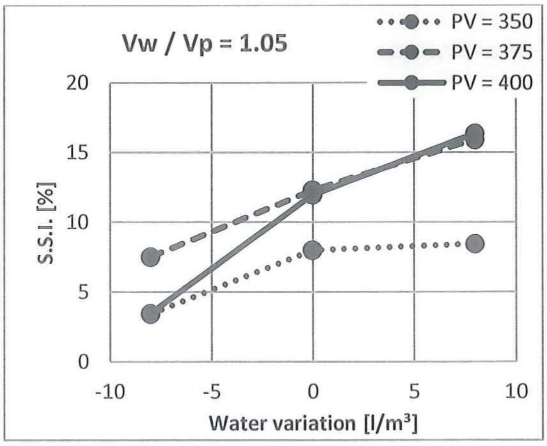

Figure 4c: Influence of the paste volume on the sieve stability

4. Discussion of influence parameters

Mixtures were designed to show a specific level of sieve stability, regardless of the fluidity of the mixture. As static segregation must be avoided in all cases, the S.S.I. was chosen as "reference mix design parameter". The conclusions of this study may therefore deviate from other results in literature.

4.1. Workability tests for the robustness

Variations induced by changes in the water content affect the filling ability, the passing ability, and the segregation resistance and may result in a rejected mixture. Because a lack of robustness of an SCC mixture is most often not caused by the three key characteristics of SCC at the same time, it is not evident to grasp the variations of the slump flow, V-funnel time, L-box ratio, and sieve stability index into one global '*robustness value*'. A better approach is to judge robustness of each mixture based on its most critical parameter: a poor flowability or a too viscous and sticky mixture when the mixture contains 8 l/m³ less water; or a severe segregation of the coarse aggregates or extreme bleeding occurring when 8 l/m³ water in excess is added to the mixture.

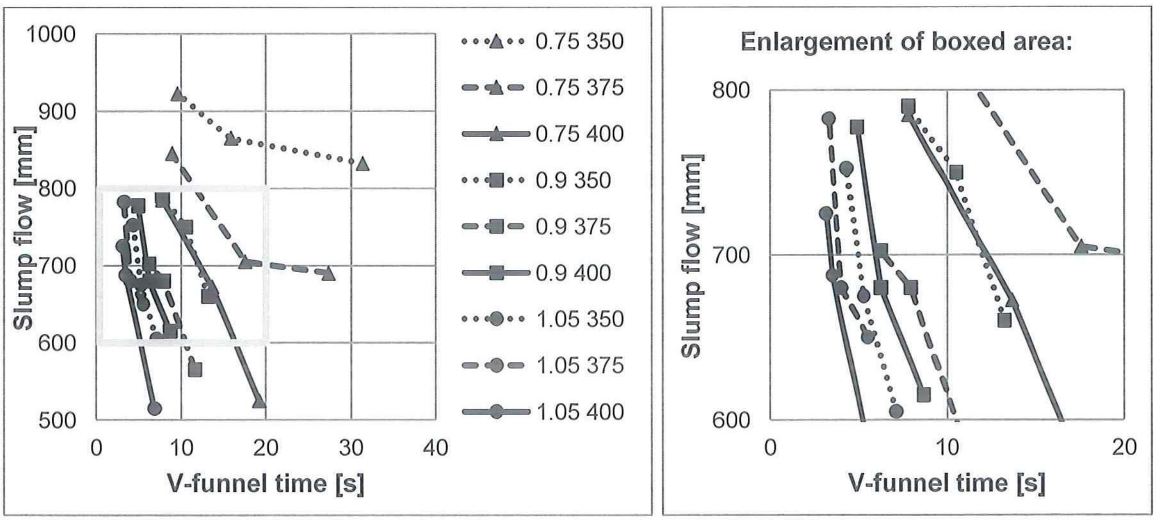

Figure 5: The robustness of all mixtures illustrated in a workability box

4.2. Influence of the paste volume

When the paste volume increases, the robustness to variations in the water content of the slump flow and S.S.I. decreases while the sensitivity of the V-funnel time is constant (Table 4 and Figure 3 to 5). As shown in Figure 5, the SCC mixtures with a higher paste volume (full lines) have a lower slump flow to achieve similar stability and are thus more sensitive to a poor flowability when the water dosage is decreased by 8 l/m³ or have a more than proportional increase in S.S.I. when 8 l/m³ water is added to the mixture.

4.3. Influence of the volumetric water-to-powder ratio

The robustness determined by changes in the V-funnel time increases when the water-to-powder ratio increases (Table 4, Figure 3, and Figure 5, lines with circles). Because the superplasticizer dosage added to the mixtures decreases with a higher water-to-powder ratio to achieve similar stability, the resulting effect on the sensitivity of the slump flow and S.S.I. is rather limited. Mixtures with a higher water-to-powder ratio have a lower plastic viscosity, making them more dependent on the yield stress to assure a stable mix design. Therefore, the robustness of these mixtures should be assured by increasing the aggregates volume and thus reducing the paste volume. When the water-to-powder ratio of a mixture is rather low, the plastic viscosity might become too high when reducing water by 8 l/m³ and the robustness should be guaranteed by a larger paste volume. The paste volume, however, should also not be too high, since this increases the sensitivity of the slump flow of the mixture.

5. Recommendations

Every application of SCC imposes specific demands towards the mix design of the concrete [24]. In order to combine specific workability demands with a sufficient robustness, the following is recommended regarding the paste volume and water-to-powder volume combination while assuming the stability of the mixture, summarized in Table 5.

Table 5: The recommended paste volume and water-to-powder ratio depended on the application

Application	Recommended paste volume	Recommended volumetric water-to-powder ratio
Large horizontal elements (floors and plates)	Low	High
Long horizontal elements (reinforced beams)	Low	Intermediate
Long vertical elements (walls)	Intermediate	Low
Slender vertical elements (columns)	High	Low

5.1. Large horizontal elements (floors and plates)

To facilitate the casting of large horizontal elements, SCC mixtures with high volumetric water-to-powder ratios should be used. Because the stability of such a mixture is provided by its high yield stress, the robustness can be improved by decreasing the paste volume of the mixture.

5.2. Long horizontal elements (reinforced beams)

A slow, but far flowing SCC mixture with a low paste volume and low water-to-paste ratio should be applied. In such a mixture, the stability is achieved by the high plastic viscosity. With a sufficiently high but not too high volumetric water-to-powder ratio, the needed robustness concerning changes in the water content is achieved.

5.3. Long vertical elements (walls)

In order to flow slowly and without segregation in between the reinforcement of long vertical elements, mixtures should have a low yield stress and a high plastic viscosity for its segregation resistance. The high plastic viscosity can be achieved with a low volumetric water-to-powder ratio. A maximum robustness is achieved by a higher paste volume, which should not be too high preventing the yield stress from becoming dominant and thus increasing the sensitivity to an too low flowability.

5.4. *Slender vertical elements (columns)*

In columns and slender walls, the mixture should have a high plastic viscosity and without specific demands towards the yield stress. Because the stability to segregation can be provided by a combination of an intermediate plastic viscosity and yield stress, the mixture needs a low volumetric water-to-powder ratio to obtain the required plastic viscosity and a relatively high paste volume.

6. Conclusions

An experimental program including nine SCC mix compositions with different paste volumes and volumetric water-to-powder ratio's demonstrates that the robustness of SCC should be tested with several workability parameters in order to determine the most critical parameter of the mixture for a specific application. Because the L-box ratio does not always provide clear trends, the analysis in this experimental program is based on the slump flow, V-funnel, and sieve stability measurements. For all mixtures, the superplasticizer dosage was adjusted to achieve a specific stability level (S.S.I. = 10±2%).

The robustness of the slump flow increases when the paste volume decreases, because mixtures with a lower paste volume depend mainly on their larger aggregate volume in order to obtain sufficient segregation resistance. The paste volume only has a minor influence on the V-funnel time and its sensitivity. A lower volumetric water-to-powder ratio increases the V-funnel time and increases the risk for the mixture of becoming too viscous when a small decrease of the water content occurs. The limited influence of the water-to-powder ratio on variations of the slump flow is probably caused by the lower superplasticizer dosage of the mixtures with a higher water-to-powder ratio.

7. Acknowledgements

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Chair's Preface

The proceedings contain 171 papers across 14 themes. All the papers included in the proceedings have been selected on the basis of least two peer reviews which were provided by independent reviewers (referees), who were experts in the subject field of the paper. We are grateful to the independent reviewers for their time and effort in reviewing the papers and providing reviews in a timely manner.

Professor Jay Sanjayan
Swinburne University of Technology
Conference Chair

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