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Publication date
2016

Document Version
Final published version

Published in
Proceedings 8th International RILEM Symposium on Self-Compacting Concrete

Citation (APA)
van der Vurst, F., Lesage, K., Grunewald, S., Vandewalle, L., Vantomme, J., & Schutter, G. (2016). Investigation on the Mechanisms Governing the Robustness of Self-Compacting Concrete at Paste Level. In K. H. Khayat (Ed.), *Proceedings 8th International RILEM Symposium on Self-Compacting Concrete* (pp. 143-155). RILEM Publications S.A.R.L..

Investigation on the Mechanisms Governing the Robustness of Self-Compacting Concrete at Paste Level

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Abstract In spite of the many advantages, the use of self-compacting concrete (SCC) is currently widely limited to application in precast factories and situations in which external vibration would cause large difficulties. One of the main limitations is the higher sensitivity to small variations in mix proportions, material characteristics and procedures, also referred to as the lower robustness of SCC compared to vibrated concrete. This paper investigates the mechanisms governing the robustness at paste level. Phenomenological aspects are examined for a series of paste mixtures varying in water film thickness and superplasticizer-to-powder ratio. The impact of small variations in the water content on the early-age structural buildup and the robustness of the paste rheology is investigated using rotational and oscillating rheometry.

Key words: *Self-compacting concrete, SCC, Robustness, Sensitivity, Rheology, Storage Modulus.*

Introduction

Self-compacting concrete (SCC) is a high performance concrete, characterized by the absence of the need of external compaction. As a result, less construction errors are made and significantly less man effort is required. However, despite the many benefits of SCC, the use in actual structures is mainly limited to precast concrete products and situations requiring a high flowability or in which external compaction would result in large difficulties. One of the major limitations for the use of SCC is its lower robustness compared to vibrated concrete, which is its sensitivity to small changes in the material properties, material proportions, or production methods.

This lower robustness imposes a more rigorous quality control demand on material properties and mix proportioning, skilled and experienced staff, and a better understanding of the mix design. Regarding the mix design, the following trends have been observed:

- A surplus of fines in the aggregate grading curve results in a higher robustness of SCC [1, 2]. The surplus of fines prevents the coarse aggregate particles from dominating the rheology.
- In SCC having a high plastic viscosity, the robustness against small variations in the water content increases as the amount of powder in the mixture is high [2, 3]. For SCC with a low plastic viscosity, an opposite trend is observed [3].
- An increase of the water-to-powder ratio increases the robustness of the V-funnel flow-time against variations in the water content [3, 4]. However, Kwan and Ng [1] have shown that a lower water-to-powder ratio increases the robustness of the slump flow against variations in the superplasticizer content. More fundamental research on this topic is necessary.
- The choice of superplasticizer [5, 6] and VMA [4, 6, 7] also affects the robustness. The addition of a VMA in the mix design can increase or decrease the robustness of the mixture [2-4, 7].
- A possible link between the thixotropy and robustness has been suggested [8, 9]. Low alkali cement is also reported to be less robust than high alkali cement [10]. Low alkali cement contains less SO_4^{2-} and C_3A, which results in a lower heat of hydration and less structural buildup [11].

Although many other parameters and influences can cause the rejection of a SCC batch [12-14], this experimental program focusses on variations in the water content. Variations in the water content have the largest impact on the rheology in concrete plants since the dosage of admixture and powders is measured very precisely and variations in the properties and grading curve of sand and gravel have a relatively smaller impact [15]. According to the European guidelines [16], a good SCC mix design should allow variations of 5 to 10 l/m^3 in the water content, which corresponds with about 3 to 6% of the water content. The ACI 117-90 and EN 117-90 codes allow variations up to 3% of the water content during the industrial production of concrete.

In this study, the Water Film Thickness (WFT) of all mixtures was evaluated. According to Li and Kwan [17], the water in fresh concrete can be divided into two parts: the filling water which fills the voids in between the solid particles, and the excess water which forms a water film on the surface of the solid particles and contributes to the fluidity of the fresh concrete. The WFT can be calculated using Equations 1-3 (Table I: Definition of parameters). The maximum packing density ϕ_{max} is calculated based on the maximum possible density of the paste obtained by variations in the water content.

$$WFT = \frac{u_w - u_{min}}{A_s} \quad \text{(Eq. 1)}$$

$$u_{min} = \frac{1-\phi_{max}-\varepsilon_a(\phi_{max})}{\phi_{max}} \quad \text{(Eq. 2)}$$

$$u_w = \frac{1-\phi-\varepsilon_a(\phi)}{\phi} \quad \text{(Eq. 3)}$$

Table I. Definition of the parameters used in Equations 1 to 3

Symbol	Unit	Name	Meaning
WFT	[m]	Water Film Thickness	Thickness of the excess water layer covering the solid particles.
ϕ	[%]	Packing density	The volume of solids divided by the bulk volume
ϕ_{max}	[%]	Maximum packing density	The maximum possible packing density possible for this mixture under varying water content.
$\varepsilon_a(\phi)$	[%]	Air content	The volume of air divided by the bulk volume.
u_w	[%]	Water ratio	The volume of water divided by the volume of solids.
u_{min}	[%]	Minimum voids ratio	The water ratio corresponding with the maximum packing density.
A_s	[m²/m³]	Specific surface area of the solids	The total surface of al solids in one volumetric unit.

When performing tests on paste, the shear forces during mixing and testing have a different order of magnitude compared to the concrete level [18, 19]. This causes differences in the flocculation of fines [20], the hydration speed [21], the thixotropic behavior [22], and relationships are difficult to establish between workability tests on paste and concrete. The investigated parameters might also affect the robustness of the stability against segregation. As a result, extrapolations from paste level to concrete level should be treated with great prudence.

Experimental setup

In order to investigate the influence of the water film thickness and paste fluidity on the robustness of the rheology against small variations in the water content, nine self-compacting pastes, varying in water-to-powder volumetric ratio (0.85, 0.90, and 0.95) and superplasticizer dosage (0.118%, 0.159%, and 0.200% of the cement weight) were tested. In order to cover a wider range of WFT, four additional mixtures were tested with water-to-

Table II. Chemical composition of the cement and limestone filler

	Cement I 52.5 N [%]	Limestone filler [%]
CaO	63.01	0.00
$CaCO_3$	0.00	98.8
SiO_2	18.55	0.11
Al_2O_3	5.83	0.04

powder / superplasticizer dosage combinations of respectively 0.75/0.200%, 0.80/0.200%, 1.00/0.159%, and 1.00/0.118%. The cement-to-powder ratio (by weight) was always kept at 0.6 . The material properties and grading curves of the cement and limestone are summarized in Figure 2 and Table II. Tap water and a polycarboxylate (PCE) superplasticizer with a concentration of 35% were also used in the experiments. The specific surface of the cement and limestone were calculated based on the particle size distribution which is given in Figure 1.

Fe_2O_3	4.09	0.04
MgO	1.22	0.32
K_2O	0.60	0.00
Na_2O	0.53	0.01
SO_3	2.97	0.02
Cl^{2-}	0.086	<0.008
L.O.I.	1.24	-
Insoluble rest	0.94	-
Density	3116 kg/m³	2674 kg/m³
Specific surface	339 m²/kg	434 m²/kg

Table III summarizes all mix compositions. For each mix composition, two additional mixtures were fabricated in order to evaluate the robustness against small variations in the water content. One with 3% more water, and one with 3% less water. Each mixture was made according to the mixing and testing procedure given in Table IV in a Hobart mixer.

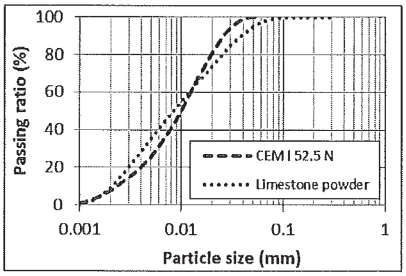

Figure 1. Grading curve of the cement and limestone powder

Table III. Mix proportions of the 14 reference self-compacting paste mixtures

Mix nr	Water-to-powder ratio	Super-plasticizer dosage	Cement	Limestone powder	Water	Super-plasticizer dosage
	[-]	[%]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]
1	0.85	0.118	948	632	459	1.12
2	0.90	0.118	923	615	474	1.09
3	0.95	0.118	899	600	487	1.06
4	1.00	0.118	877	585	500	1.03
5	0.85	0.159	948	632	459	1.51
6	0.90	0.159	923	615	474	1.47
7	0.95	0.159	899	600	487	1.43
8	1.00	0.159	877	585	500	1.39
9	0.75	0.200	1002	668	429	2.00
10	0.80	0.200	974	650	444	1.95
11	0.85	0.200	948	632	459	1.90
12	0.90	0.200	923	615	474	1.85
13	0.95	0.200	899	600	487	1.80

Table IV: Mixing and testing procedure

Time	Duration	Step	Mixing speed
0 min	1 min	Mixing of cement, limestone powder and water	140 rpm
1 min	1 min	Adding the superplasticizer	140 rpm
2 min	1 min	Mixing	285 rpm
3 min	2 min	A thin layer of paste is scraped from the mixing arm and the walls and bottom of the mixing bowl	0 rpm
5 min	1 min	Mixing	285 rpm
6 min	11 min	Rest	0 rpm
17 min	1 min	Remixing	285 rpm
18 min	2 min	Rest	0 rpm
20 min	3 min	Rotational rheometry: determination of the Modified Bingham parameters	-
25 min	45 min	Start oscillatory rheometry: measurement of G' buildup	-
29 min	1 min	Remixing	285 rpm
30 min	5 min	Measuring the density and air content	-

The Modified Bingham parameters [23] (Equation 4 and Table V) of each paste were determined using rotational rheometry in an Anton Paar MCR 201 rheometer with a wide gap concentric cylinder configuration. The inner cylinder has a radius of 20 mm, a height of 60 mm and it is covered with a sand-blasted surface; the outer cylinder has a radius of 35 mm and is provided with ribs to prevent wall slip. The rotational velocity profile, illustrated in Figure 2, consists of a preshear step, a stepwise decreasing rotational velocity profile, and the determination of a segregation point. When the torque measured during a rotational velocity step was not in equilibrium, this data point was not used for the analysis. A plug flow correction was performed when plug flow occurred [24].

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} + c \cdot \dot{\gamma}^2 \qquad \text{(Eq. 4)}$$

Table V: Symbols used in the Modified Bingham equation (Eq. 4)

Symbol	Unit	Meaning
τ	[Pa]	Shear stress
$\dot{\gamma}$	[s^{-1}]	Shear rate
τ_0	[Pa]	Yield stress
μ	[Pa.s]	Modified Bingham linear term
c	[Pa.s^2]	Modified Bingham second order term

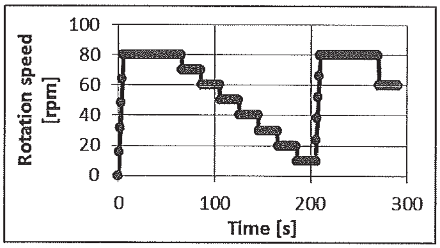

Figure 2. Rotational velocity profile applied in rotational rheometry

Oscillatory rheometry was used to monitor the structural buildup of the paste sample at rest. The storage modulus G' evolution was measured using an Anton Paar MCR 201 rheometer with a vane in cylinder setup. In these experiments, a vane with a diameter of 15 mm and a height of 40 mm vibrates within a small angle and a frequency of 1 Hz in an outer cylinder with a radius of 35 mm. After destroying the structure in a 2 minutes time sweep with a strain of 50% (above the critical strain), the structural buildup inside the paste was monitored in a time sweep with a small strain of 0.1% (below the critical strain) for 20 minutes using the storage modulus G' [25-27]. A typical example of a measurement is shown in Figure 3.

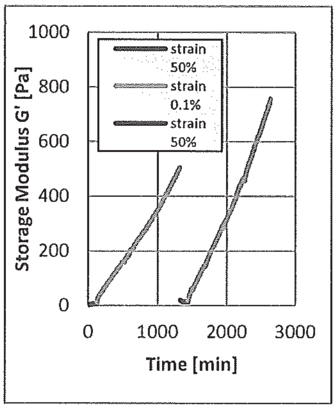

Figure 3. Monitoring of the Storage Modulus G' using oscillatory rheology

Results and Discussion

The measured properties of the 13 reference mixtures are listed in Table VI. The range of covered WFT values is illustrated in Figure 4 and are based on the maximum packing densities of the powder measured in wet condition. A smaller dosage of superplasticizer leads to a higher maximum packing densities and smaller WFT values at a similar water-to-powder ratio. A clear link between the WFT and the rheology of the mixture can be observed in Figure 5.

Table VI. Properties of the reference self-compacting paste mixtures

Mix nr	Water-to-powder ratio	Superplasticizer dosage	Max. packing density	Air content	WFT	Yield stress	MB linear term	MB 2nd order term	Increase in G' (1)	Increase in G' (2)
	[-]	[%]	[%]	[%]	[μm]	[Pa]	[Pa.s]	$[Pa.s^2]$	[Pa]	[Pa]
1	0.85	0.118	0.577	1.0	0.188	16.38	1.59	0.0000	1073	1873
2	0.90	0.118	0.577	0.8	0.198	7.05	0.85	0.0005	711	1218
3	0.95	0.118	0.577	0.5	0.276	2.55	0.39	0.0024	717	1665
4	1.00	0.118	0.577	0.5	0.304	2.17	0.30	0.0012	514	1220
5	0.85	0.159	0.589	0.4	0.209	2.68	0.41	0.0048	322	365

6	0.90	0.159	0.589	0.5	0.236	2.23	0.32	0.0034	306	364
7	0.95	0.159	0.589	0.2	0.308	0.62	0.28	0.0018	302	411
8	1.00	0.159	0.589	0.2	0.340	0.49	0.14	0.0031	225	521
9	0.75	0.200	0.603	0.6	0.151	8.71	0.68	0.0086	701	1007
10	0.80	0.200	0.603	0.5	0.209	3.22	0.28	0.0066	265	462
11	0.85	0.200	0.603	0.3	0.267	0.77	0.32	0.0047	206	202
12	0.90	0.200	0.603	0.1	0.289	0.00	0.22	0.0031	256	504
13	0.95	0.200	0.603	0.3	0.355	0.00	0.18	0.0022	382	2836

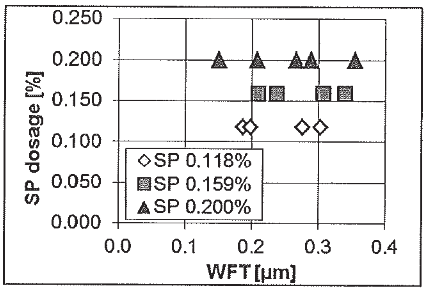

Figure 4. The range of WFT covered in this experimental program

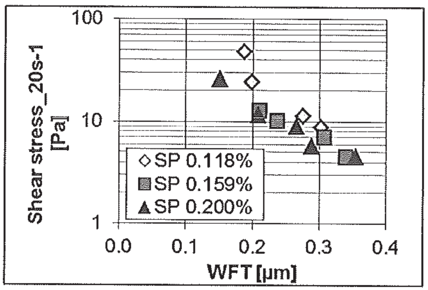

Figure 5. Influence of the WFT on the rheology

The robustness against small variations in the water content is tested by changing the water content with ±3%. Table VII summarizes the impact on the rheological characteristics. Because the variations in the test results should be compared by the value of the reference mixture, all changes are expressed as percentages.

Figure 6 illustrates an increasing water-to-powder ratio or superplasticizer dosage increases the robustness of the shear stress at a shear rate of 20 s^{-1} ($\tau(20\,s^{-1})$. A similar trend can be observed using the shear stress inclination at 20 s^{-1} ($\frac{d\tau}{d\dot{\gamma}}(20\,s^{-1})$. The effect on the yield stress seems to be independent of water-to-powder ratio (similar slopes are obtained).

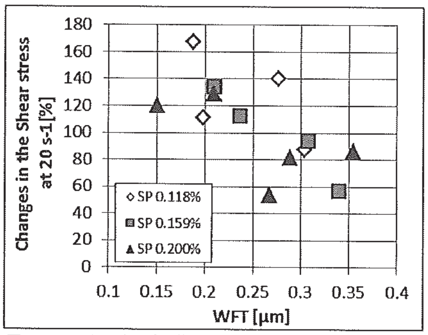

Figure 6. The influence of the WFT and

superplasticizer dosage on the robustness of the rheology

Table VII. Robustness of the reference mixtures against small changes in the water content

Mix nr	Water-to-powder ratio	Superplasticizer dosage	WFT	Changes in the shear stress at 20s-1	Changes in the yield stress	Changes in the shear stress inclination at 20s-1
	[-]	[%]	[µm]	[%]	[%]	[%]
1	0.85	0.118	0.188	167	176	160
2	0.90	0.118	0.198	111	126	105
3	0.95	0.118	0.276	140	201	115
4	1.00	0.118	0.304	87	118	73
5	0.85	0.159	0.209	134	257	77
6	0.90	0.159	0.236	112	196	91
7	0.95	0.159	0.308	94	313	75
8	1.00	0.159	0.340	57	121	51
9	0.75	0.200	0.151	120	118	95
10	0.80	0.200	0.209	128	199	89
11	0.85	0.200	0.267	53	245	48
12	0.90	0.200	0.289	81	248	57
13	0.95	0.200	0.355	86	90	73

Figure 7 shows the changes of the rheology in a rheogram. A logarithmic scale is used to illustrate the graphs because the impact of a change in the rheological parameters depends on the value of the parameter itself. A change of 0.1 Pa on the yield stress has a more pronounced impact on a mixture with a yield stress of 0.2 Pa than on a mixture with a yield stress of 50 Pa. Based on the concept of robustness area described by Billberg and Westerholm [7] on concrete rheograms, a definition of robustness is proposed. Assuming a rectangle surrounding the changes in rheology on the logarithmic graphs in Figure 8 illustrates the sensitivity of pastes to small changes in the water content, the definition of the robustness value is defined as one divided by the area of the rectangle in a logarithmic scale (Equation 5). The higher R is, the more robust is a paste system.

$$R = \frac{1}{log\left(\frac{\tau_{0,max}}{\tau_{0,min}}\right) * log\left(\frac{\mu_{max}}{\mu_{min}}\right)} \qquad \text{(Eq. 5)}$$

This definition of the robustness allows to compare the combined changes relative to the original values of the two parameters describing the rheological behavior of the paste. Table VIII summarizes the robustness value R of all mixtures. The table also summarizes the increases in storage modulus G' during the first and second 20 minutes of structural buildup during the oscillatory rheometry (G'_1 and G'_2).

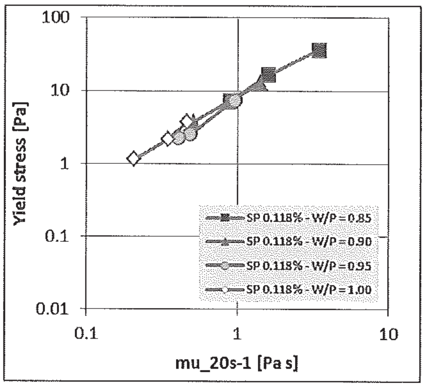

Figure 7a. Robustness of the rheology illustrated in a rheogram (SP 0.118%)

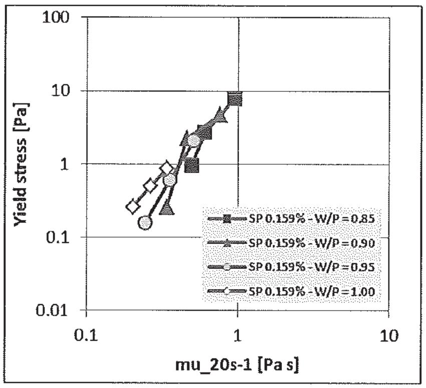

Figure 7b. Robustness of the rheology illustrated in a rheogram (SP 0.159%)

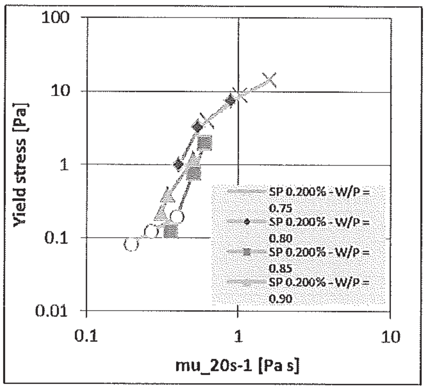

Figure 7c. Robustness of the rheology illustrated in a rheogram (SP 0.200%)

Table VIII. The robustness evaluation of all reference mixtures

Mix nr	Water-to-powder ratio	Superplasticizer dosage	WFT	Yield stress	Inclination of the shear stress at 20s-1	Increase in G'1	Increase in G'2	Robustness value R
	[-]	[%]	[µm]	[Pa]	[Pa]	[Pa]	[Pa]	[-]
1	0.85	0.118	0.188	16.38	1.59	1073	1873	2.44
2	0.90	0.118	0.198	7.05	0.87	711	1218	4.28
3	0.95	0.118	0.276	2.55	0.49	717	1665	5.22
4	1.00	0.118	0.304	2.17	0.35	514	1220	5.59
5	0.85	0.159	0.209	2.68	0.60	322	365	3.81

6	0.90	0.159	0.236	2.23	0.46	306	364	2.29
7	0.95	0.159	0.308	0.62	0.35	302	411	2.81
8	1.00	0.159	0.340	0.49	0.26	225	521	8.69
9	0.75	0.200	0.151	8.71	1.03	701	1007	4.40
10	0.80	0.200	0.209	3.22	0.54	265	462	3.38
11	0.85	0.200	0.267	0.77	0.50	206	202	3.66
12	0.90	0.200	0.289	0.00	0.35	256	504	6.45
13	0.95	0.200	0.355	0.00	0.27	382	2836	8.99

Based on the robustness definition, the following trends and influence factors are observed:

- Figures 8 and 9 illustrate the correlation between the robustness and the water-to-powder volumetric ratio (SP 0.118%: $R^2 = 0.91$; SP 0.159%: $R^2 = 0.45$; SP 0.200%: $R^2 = 0.68$) or a higher WFT ($R^2 = 0.47$). The relation between the water-to-powder ratio and the robustness depends on the superplasticizer dosage. Similar trends can be found based on the ratio of the packing density to the maximum packing density ϕ/ϕ_{max} of the mixtures ($R^2 = 0.42$).
- No clear influence of the yield stress τ_0, inclination of the shear stress at 20 s^{-1} $\frac{d\tau}{d\dot{\gamma}}(20\ s^{-1})$, or the shear stress at 20 s^{-1} $\tau(20\ s^{-1})$ on the robustness is observed.

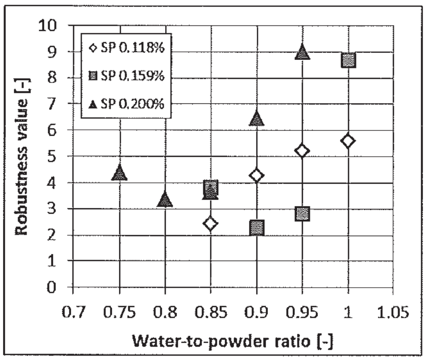

Figure 8. The influence of the water-to-powder ratio on the robustness value

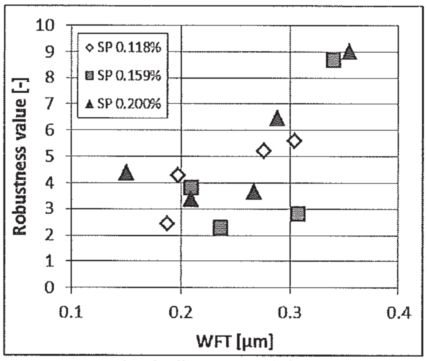

Figure 9. The influence of the WFT on the robustness value

- In Figure 10, the relation between the sensitivity of the rheology and the structural buildup as measured by the storage modulus G' buildup at rest is illustrated. Mixtures with a higher G' buildup rate were more sensitive to changes in the shear rate and the inclination of the shear rate of mixtures (Table VIII). However, no relation between the structural buildup and the robustness value can be established.

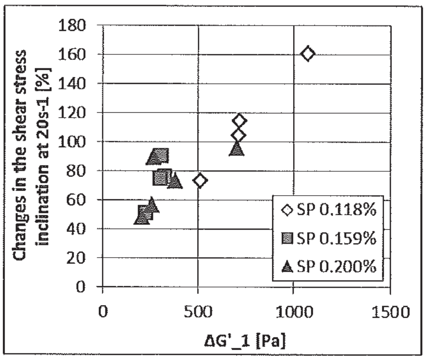

Figure 10. Influence of the structural buildup on the robustness of the shear stress at 20 s^{-1}

The observed relation between the water-to-powder ratio or WFT and the rate of structural buildup is valid on paste level. Because the pastes were mixed in the absence of the ball-bearing effect of aggregates and in a Hobart mixer, the hydration reaction rate differs from a paste mixed inside a concrete mixture.

Conclusions

Based on an extensive experimental program, some possible mechanisms governing the robustness of the paste rheology against small variations in the water content have been investigated. Thirteen mixtures varying in water-to-powder volumetric ratio and superplasticizer dosage were subjected to variations of ±3% of their water dosage. Higher water-to-powder ratios resulted in a higher water film thicknesses (WFT), and in more robust mixtures. A higher superplasticizer dosage resulted in a higher WFT and also more robust mixtures. A higher early age structural buildup as measured by the increase in storage modulus G' at rest resulted in less robust mixtures. No clear influence of the viscosity of the mixtures was observed.

References

[1] Kwan AKH, Ng IYT. Optimum superplasticiser dosage and aggregate proportions for SCC. Magazine of Concrete Research. 2009;61(4):281-92.

[2] Bonen D, Deshpande Y, Olek J, Shen L, Struble L, Lange DA, et al. Robustness of self-consolidating concrete. In: De Schutter G, Boel V, eds. *5th International RILEM Symposium on Self-Compacting Concrete*. Ghent, Belgium: RILEM Publications SARL 2007:33-42.

[3] Van Der Vurst F, Grünewald S, Feys D, Vandewalle L, Vantomme J, De Schutter G. Interaction between Rheology and Robustness of Fresh Self-Compacting Concrete. in press. 2016.

[4] Billberg PH. Influence of powder type and VMA combination on certain key fresh properties of SCC. In: Wallevik O, Khrapko M, eds. *9th International Symposium on High Performance Concrete*. Rotorua, New Zealand: New Zealand Concrete Society 2011.

[5] Haldenwang R, Fester VG. The influence of different superplasticisers on the flowability and reproducibility of a SCC mix. In: Wallevik O, Khrapko M, eds. *9th International Symposium on High Performance Concrete*. Rotorua, New Zealand: New Zealand Concrete Society 2011.

[6] Naji S, Hwang S-D, Khayat KH. Robustness of self-consolidating concrete incorperating different viscosity-enhancing admixtures. ACI Materials Journal. 2011;108(4):432-8.

[7] Billberg P, Westerholm M. Robustness of fresh VMA-modified SCC to varying aggregate moisture. NCR Journal. 2008;38(7):103-19.

[8] Bonen D, Deshpande Y, Olek J, Shen L, Struble L, Lange DA, et al. Chapter 1. Robustness of SCC. In: Lange DA, ed. *Self-consolidating concrete*. Urbana, IL, U.S.A.: The Center for Advanced Cement Based Materials (ACBM) 2007:4-22.

[9] Bouras R, Chaouche M, Kaci S. Influence of viscosity-modifying admixtures on the thixotropic behaviour of cement pastes. Applied Rheology. 2008;18(4):45604-1 - -8.

[10] Nkinamubanzi P-C, Aïtcin P-C. Cement and superplasticizer combinations: Compatibility and robustness. Cement, Concrete and Aggregates. 2004;26(2):102-9.

[11] Ferron RPD. Formwork pressure of self-consolidating concrete: influence of flocculation mechanism, structural rebuilding, thixotropy, and rheology. *Department of Civil and Environmental Engineering*. Evanston, IL, USA: Northwestern University 2008:Doctoral thesis.

[12] Nunes S, Milheiro-Oliveira P, Sousa Coutinho J, Figueiras J. Rheological characterization of SCC mortars and pastes with changes induced by cement delivery. Cement & Concrete Composites. 2011;33(1):103-15.

[13] Feys D, Asghari A, Ghafari E, Ley Hernandez AM, Van Der Vurst F, De Schutter G. Influence of mixing procedure on robustness of self-consolidating concrete. Center for Transportation Infrastructure and Safety 2014.

[14] Yamada K, Yanagisawa T, Hanehara S. Influence of temperature on the dispersibility of polycarboxylate type superplasticizer for highly fluid concrete. In: Skarendahl A, Petersson Ö, eds. *First International RILEM Symposium on Self-Compacting Concrete*. Stockholm, Sweden: RILEM Publications 1999:437-48.

[15] Rigueira JW, García-Taengua E, Serna-Ros P. Self-consolidating concrete robustness in continuous production regarding fresh and hardened state properties. ACI Materials Journal. 2009;106(3):301-7.

[16] BIBM - CEMBUREAU - EFCA - EFNARC - ERMCO. The European Guidelines for Self-Compacting Concrete - Specification, Production and Use. 2005.

[17] Li LG, Kwan AKH. Concrete mix design based on water film thickness and paste film thickness. Cement and Concrete Composites. 2013;39(5):33-42.

[18] Yang M, Jennings HM. Influences of mixing methods on the microstructure and rheological behavior of cement pastes. Advanced Cement Based Materials. 1995;2(2):70-8.

[19] Williams DA, Saak AW, Jennings HM. The influence of mixing on the rheology of fresh cement paste. Cement and Concrete Research. 1999;29(9):1491-6.

[20] Takada K, Walraven JC. Influence of mixing efficiency on the properties of flowable cement pastes. In: Ozawa K, Ouchi M, eds. *Second International Symposium on Self-Compacting Concrete*. Tokyo, Japan 2001:545-54.

[21] Juilland P, Kumar A, Gallucci E, Flatt RJ, Scrivener KL. Effect of mixing on the early hydration of alite and OPC systems. Cement and Concrete Research. 2012;42(9):1175-88.

[22] Assaad J, Khayat KH. Assessment of thixotropy of self-consolidating concrete and concrete-equivalent-mortar - effect of binder composition and content. ACI Materials Journal. 2004;101(5):400-8.

[23] Feys D, Wallevik JE, Yahia A, Khayat K, Wallevik OH. Extension of the Reiner-Riwlin equation to determine modified Bingham parameters measured in coaxial cylinders rheometers. Materials and Structures. 2013;46(1-2):289-311.

[24] Wallevik JE. Rheology of particle suspensions - Fresh concrete, mortar and cement paste with various types of lignosulfonates. *Department of Structural Engineering*. Trondheim, Norway: The Norwegian University of Science and Technology (NTNU) 2003:Doctoral thesis.

[25] Roussel N, Ovarlez G, Garrault S, Brumaud C. The origins of thixotropy of fresh cement pastes. Cement and Concrete Research. 2012;42(1):148-57.

[26] Lesage K. Interactions between cement and combined concrete admixtures - The influence on cement paste rheology. *Department of Civil Engineering*. Leuven, Belgium: University of Leuven 2014:Doctoral thesis.

[27] Betioli AM, Gleize PJP, Silva DA, John VM, Pileggi RG. Effect of HMEC on the consolidation of cement pastes: isothermal calorimetry versus oscillatory rheometry. Cement and Concrete Research. 2009;39(5):440-5.