Influence of Pumping on the Fresh Properties of Self-Compacting Concrete

D Feys [1], G De Schutter[1] and R Verhoeven[2]

[1] Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering, Ghent University, Belgium

[2] Hydraulics Laboratory, Department of Civil Engineering, Faculty of Engineering Ghent University, Belgium

This is an original scientific paper published in Concrete Beton, journal of the Concrete Society of Southern Africa, in Volume 129, pp 8-12 November 2011.

Journal Contact Details:
PO Box 75364
Lynnwood Ridge
Pretoria, 0040
South Africa
+27 12 348 5305

admin@concretesociety.co.za
www.concretesociety.co.za

Influence of pumping on the fresh properties of self-compacting concrete

D Feys, *Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering, Ghent University, Gent, Belgium Hydraulics Laboratory, Department of Civil Engineering, Faculty of Engineering, Ghent University, Gent, Belgium*

G De Schutter, *Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering, Ghent University, Gent, Belgium*

R Verhoeven, *Hydraulics Laboratory, Department of Civil Engineering, Faculty of Engineering, Ghent University, Gent, Belgium*

ABSTRACT: Pumping of concrete is a frequently applied casting process. For traditional concrete, slump losses have been reported in literature, but the real cause is still unknown. In case of self-compacting concrete, it is not known how the fresh properties evolve due to pumping. This paper will describe the evolution of the fresh properties of Self Compacting Cement (SCC) due to pumping operations, in which the velocity is increased stepwise. Two different effects modify the fresh properties: structural breakdown and an increase in air content. Both effects cause a decrease in viscosity, which is translated in a lower V-funnel flow time and lower pressure losses during pumping. On the other hand, structural breakdown and the increase in air content have an opposite influence on the yield stress. If structural breakdown dominates, the yield stress decreases; if the effects of the increase in air content dominate, yield stress increases. In the first case, as both yield stress and viscosity decrease, segregation can be provoked. In the second case, due to the increase in yield stress, the filling ability of the SCC is reduced, which can lead to improper filling of the formwork. The results show a trend that the more fluid SCCs tend to segregate and the less fluid SCCs tend to lose even more fluidity. Furthermore, the magnitude of these effects appears to increase with increasing velocity in the pipes.

1. INTRODUCTION

On site, concrete can be placed in the formwork in two different ways: by means of a bucket, inducing a discontinuous casting process, or by means of pumping. In case of pumping, the casting rate can increase and savings in time and labour costs can be achieved. On the other hand, very few studies on the pumping of concrete exist (Kaplan, 2001; Chapdelaine, 2007) and the fundamental understanding of this Self Compacting Cement process has not been completely achieved. The research field is still completely open as this type of concrete is more fluid compared to the ordinary vibrated concrete types. As a result, the flow behaviour of SCC in pipes is reported to be different (Feys, 2009).

Although from a scientific point of view, the phenomena occurring during pumping of SCC are not completely understood yet, this casting process is applied daily. Sometimes, it is reported that the fresh properties are significantly influenced by the pumping operation, but also in case of ordinary concrete. This paper will describe the test method used and the results of the influence of pumping on the fresh properties of SCC. Before the description of the pumping tests, a short introduction will be given dealing with the rheological properties of fresh SCC.

2. RHEOLOGY

2.1 Steady state

In steady state conditions, during which no time-dependent effects influence the results, fresh concrete in general can be described as a Bingham material, showing a linear relationship between the shear stress (related to the pressure loss) and the shear rate (related to the velocity gradient), according to equation 1 (Tattersall & Banfill, 1983).

$$\tau = \tau_o + \mu_p \cdot \dot{\gamma} \qquad (1)$$

where: τ = shear stress (Pa)
τ_o = yield stress (Pa)
μ_p = plastic viscosity (Pa s)
$\dot{\gamma}$ = shear rate (s^{-1})

As can be seen, at least two parameters are needed to describe the fresh behaviour of concrete: the yield stress, which is the resistance to the initiation of flow; and the plastic viscosity, which is the resistance to a further acceleration of the flow.

When comparing ordinary concrete and SCC, it is observed that the yield stress of SCC is much lower in order to achieve the self-compactability and that the viscosity of the SCC is generally higher to assure the segregation resistance of the SCC-mixture (Wallevik, 2003a).

Note that under some circumstances the rheological behaviour of SCC is non-linear, but this is beyond the scope of this paper (Feys et al., 2009).

2.2 Time dependent properties

In time, the obtained rheological properties vary, of which the cause can be theoretically divided into three main parts: thixotropy, structural breakdown and loss of workability (Wallevik, 2003b; Wallevik, 2009).

Thixotropy is defined as the reversible breakdown and build-up of connections between small particles in the concrete. The 'structuration state (λ)' represents the amount of connections. The lower λ, the less connections, the more fluid the concrete (Roussel, 2006).

Structural breakdown is known as the disruption of chemical connections under the influence of shear. In contrast to thixotropy, structural breakdown does not show, strictly speaking, any rebuild over time (Tattersall & Banfill, 1983).

Loss of workability represents the increase in number of connections of any type in the concrete, which can no longer be broken by the acting shearing forces. As a result, the structuration state permanently increases and the concrete becomes more stiff. Finally, the chemical bonds become very strong transforming concrete from the liquid to the solid state.

Under influence of increasing shear, the distinction between thixotropy and structural breakdown is very difficult to make and as a result, these effects will be examined together in the discussion in this paper. The general effect of this structural breakdown 'in its broad sense', as it is considered in this paper, is that λ shows a certain equilibrium value for each applied shear rate (except for the very low shear rates), which will be achieved after a certain time. The higher the applied shear rate, the lower the equilibrium value of λ and consequently, the more fluid the concrete. For example, due to a sudden increase in shear rate, the stress shows a (mostly) exponential decrease with time, until equilibrium is reached.

2.3 Air content

In the previous sections, concrete is regarded as a homogeneous suspension. In case the sample of concrete on which the measurements are performed is sufficiently large, this assumption can be justified. But concrete does not only contain solid particles and liquid, it also contains a gas phase: air. The exact influence of air on the rheological properties of fresh concrete is currently under investigation, but at this moment, some qualitative conclusions can be drawn.

The influence of air in a liquid material (or a suspension) is governed by the capillary-number (Ca), which is the ratio of the shearing forces to the surface tension forces (eq. 2) (Rust & Manga, 2002).

$$Ca = \frac{d \cdot \mu_a \cdot \dot{\gamma}}{\Gamma} \qquad (2)$$

where: Ca = capillary-number (-)

d = bubble diameter (m)

μ_a = apparent viscosity (Pa s)

Γ = surface tension (N/m)

In case the Ca-number is low (< 1), the shearing forces are not sufficiently high to overcome the surface tension and the bubble remains spherical. As a result, the flow resistance increases with increasing air content. In the other case where Ca > 1, the bubbles deform due to the shearing forces and they align in the flow direction. Consequently, the flow resistance decreases with increasing bubble content.

3. PUMPING TESTS

3.1 Concrete pump

The concrete pump used is a standard available truck-mounted piston pump, depicted in figure 1. Inside the pump, two cylinders alternately push concrete in the pipes or pull concrete from the reservoir. Once the first cylinder is empty and the second is full, a powerful valve changes the connection between the pipes and the cylinders. The operator of the pump can vary the discharge in 10 discrete steps from 4-5 l/s (step 1) to 40 l/s (step 10). For safety reasons, step 5 has never been exceeded in the tests.

Figure 1. Concrete piston pump.

3.2 Circuit

Behind the pump, an 81m or 105m (figure 2) loop circuit has been installed by means of steel pipes with an inner diameter of 106mm. The circuit consisted of five horizontal sections, of which three were instrumented, and an inclined part. At the end of the circuit, the concrete falls inside a reservoir, which can be closed for sampling and discharge calibration, but which is mostly open. In case the reservoir is open, the concrete falls back inside the reservoir of the pump and is ready to be re-used.

Figure 2. 105 m loop circuit.

3.3 Instrumentation

In the last horizontal section of the circuit, two pressure sensors were installed in order to measure the pressure loss (figure 3). In three of five horizontal sections, including the section with the pressure sensors, strain gauges were attached to the outer pipe wall, recording the expansion and contraction, which is related to the local pressure (Kaplan, 2001). Only the results of the last horizontal section will be discussed in this paper.

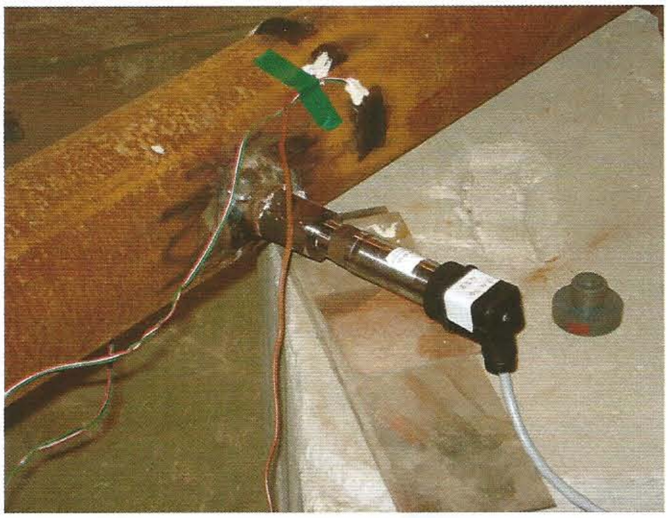

Figure 3. Pressure sensor and strain gauges.

Discharge is somewhat more complicated to measure as there is no direct tool available. On the other hand, due to the pumping mechanism, a pressure drop is observed each time the valve of the pump changes the connection (figure 4). Between two pressure drops, the total volume of one cylinder is pushed inside the pipes (which is called a stroke) and by measuring the time needed for a certain amount of strokes, discharge can be easily determined.

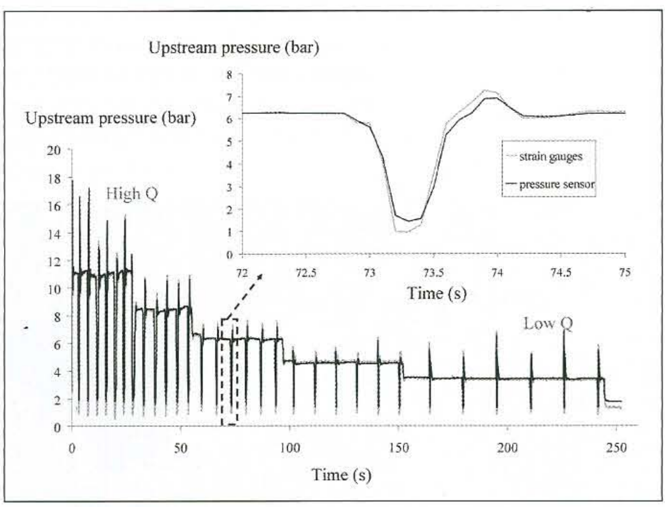

Figure 4. Determination of discharge by measuring the time needed for a certain amount of strokes. The time between two vertical spikes represents the emptying of one cylinder. The evolution of the pressure during the change of the valve is shown in the inset.

3.4 Concrete

During this part of the research programme, four SCC mixtures were pumped in the circuits described. The total amount of concrete needed per test was 3.25m³ and consequently, all concretes were produced by a ready-mix company and delivered to the lab in a time span of one hour. Mixtures 15 and 17 were commercial products of the mixing plant. Mixtures 14 and 16 were based on laboratory compositions, containing 697kg of coarse aggregates (up to 16mm), 853kg of sand, 360kg of CEM I 52.5 N (OPC) and 240kg of limestone filler. Mixture 14 contained 160ℓ of water, while mixture 16 contained 165ℓ of water per m³ of concrete. The amount of SP was adopted in order to achieve a target slump flow of 650mm in case of mixtures 14 and 15 and 700mm in case of mixtures 16 and 17. The SP were PCE-based, showing a long workability retention. For the commercial mixtures, the same sand, limestone filler and SP were used..

3.5 Testing procedure

In order to study the influence of pumping on the fresh properties of SCC, a special testing procedure was developed. It consists of three sub-cycles, repeated five times, each time increasing the maximum discharge. The sub-cycles are divided in three parts:

- Maintaining discharge constant until an equilibrium in pressure loss is observed. This can take more than 10 minutes, especially at the low discharges.
- Discharge calibration and sampling. The concrete samples were used to determine the rheological properties and to execute the standard tests on SCC, like slump flow, V-funnel, sieve stability, air content and density measurements.
- A stepwise decreasing discharge curve, maintaining each discharge for five full strokes, starting from the discharge in the first part of the sub-cycle. This procedure takes in average two minutes. At discharge step 1, which is the lowest discharge, no decreasing discharge curve was determined.

After the decreasing discharge curve, the maximal discharge is increased by one step and the sub-cycle is repeated, as shown in figure 5.

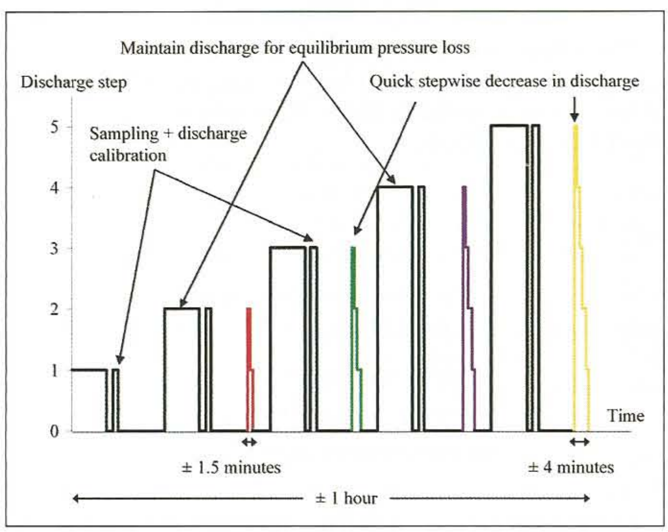

Figure 5. Testing procedure.

This procedure was executed once for mixtures 14, 16 and 17 and twice for mixture 15. For mixtures 14 and 16 and the first test on mixture 15, the discharge did not exceed step 4. For mixture 16, a small variation was applied, by repeating the step at discharge 3 for three times (step 3, step 3bis and step 3ter).

4. RESULTS

4.1 Pressure loss – discharge curves

Plotting the results of pressure loss as a function of discharge, for each equilibrium point at each discharge, and all downward curves reveals that the pressure loss at a certain discharge decreases when a discharge is applied before, which can be seen in figure 6 for mixture 14. As a result, if a higher discharge is applied, the flow resistance of the SCC in the pipes decreases. The results of the other SCC mixtures are very similar.

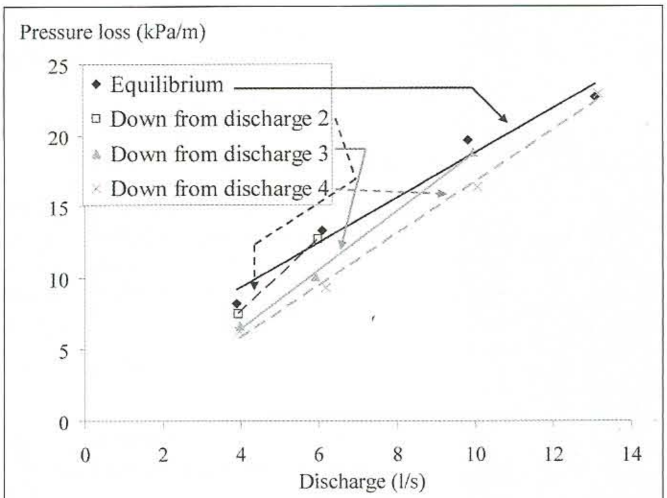

Figure 6. Pressure loss as a function of discharge, showing a lower pressure loss at a certain discharge if a higher discharge was applied before. Results from mixture 14.

4.2 Rheological measurements

The results of the rheometer tests executed on the sampled concrete indicate similar results. Although the test results are not always reliable, the general trend shows a decrease in plastic viscosity and in some cases an increase in yield stress. This confirms the pumping results as in the case of SCC, the pressure loss is mainly dependent on the viscosity of the concrete (Feys, 2009).

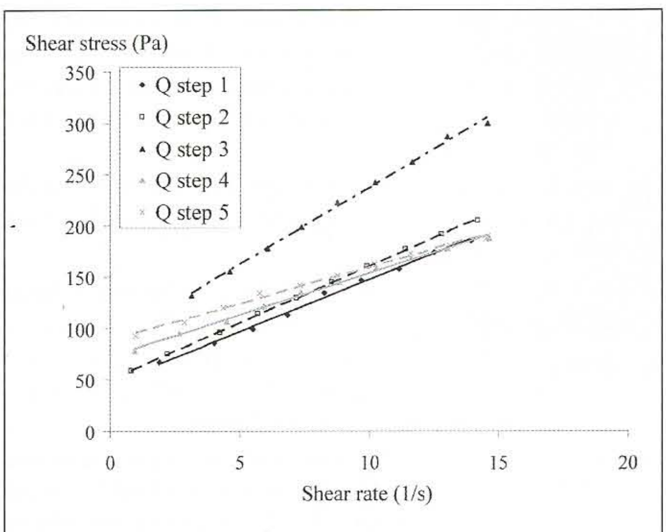

Figure 7. Rheological curves for mixture 15 – test 2, showing a clear decrease in viscosity (inclination) and increase in yield stress (intersection with shear stress axis), with increasing discharge step. Note that the results for step 3 are not reliable.

4.3 Tests on fresh SCC

The tests on fresh SCC indicate for all mixtures a decrease in V-funnel flow time. For all mixtures, except for mixture 14, an increase in air content and a decrease in density is measured. Mixtures 15 and 16 show a decreasing slump flow, while for mixture 17, slump flow remains constant. On the other hand, the sieve-(un)stability value appears to increase for mixture 17. The detailed results of all tests on fresh SCC can be found in table 1. All results are qualitatively in accordance with the rheometer results and the results of the pumping tests.

Table 1. Overview of the tests on fresh concrete for all mixtures.

	Mix 14			
	Q1	Q2	Q3	Q4
Age (hour)	**2:30**	**2:45**	**3:00**	**3:30**
Tests on fresh SCC				
Slump flow (mm)	818	758	745	658
V-Funnel (s)	5.23	6.1	3.65	5.82
Sieve Stability (%)	10.9	11.0	14.2	7.5
Air content (%)	1.6	1.8	1.6	1.5

	Mix 15 - test 1			
	Q1-1	Q1-2	Q1-3	Q1-4
Age (hour)	**1:30**	**1:45**	**2:00**	**2:10**
Tests on fresh SCC				
Slump flow (mm)	645	625	660	570
V-Funnel (s)	5.43	4.18	3.77	3.42
Sieve Stability (%)	4.2	7.0	6.6	4.0
Air content (%)	2.1	2.4	3.2	4.2

	Mix 15 - test 2				
	Q2-1	Q2-2	Q2-3	Q2-4	Q2-5
Age (hour)	**2:50**	**3:00**	**3:10**	**3:20**	**3:30**
Tests on fresh SCC					
Slump flow (mm)	525	543	505	498	445
V-Funnel (s)	3.54	3.06	3.29	3.46	3.74
Sieve Stability (%)	3.4	4.5	1.9	0.8	0.3
Air content (%)	3.7	3.9	4.6	5.0	6.2

	Mix 16					
	Q 1	Q 2	Q 3	Q 3 bis	Q 3 ter	Q 4
Age (hour)	**2:35**	**2:45**	**3:00**	**3:10**	**3:20**	**3:30**
Tests on fresh SCC						
Slump flow (mm)	670	675	655	585	620	535
V-Funnel (s)	5.24	4.02	4.78	3.72	3.76	3.89
Sieve Stability (%)	8.7	12.7	6.9	6.8	7.8	5.7
Air content (%)	1.1	1	1.4	1.3	2.2	3.9

	Mix 17				
	Q 1	Q 2	Q 3	Q 4	Q 5
Age (hour)	**1:20**	**1:30**	**1:40**	**1:50**	**2:00**
Tests on fresh SCC					
Slump flow (mm)	785	780	750	765	750
V-Funnel (s)	3.39	3.08	2.66	2.35	2.22
Sieve Stability (%)	10.5	-	11.7	15.6	18.5
Air content (%)	1.4	1.9	3.1	3.9	4.9

5. DISCUSSION

5.1 Structural breakdown

As mentioned in section 2.2, the equilibrium internal structure of the concrete decreases with increasing shear rate. As a result, the concrete becomes more fluid with increasing maximal discharge applied. This result is confirmed by the decreasing pressure losses, decreasing viscosity and decreasing V-funnel flow time. For mixture 17, the structural breakdown theory provides the ability to explain the observed segregation. Due to the decrease in viscosity and the constant yield stress, SCC becomes more sensitive to segregation. On the other hand, the structural breakdown theory is not capable of explaining the effect of increase in yield stress for mixtures 15 and 16.

5.2 Air content

For all mixtures, except mixture 14, the air content increases with increasing discharge up to values of around 5 – 6%. For these values, the importance of the air bubbles on the rheological properties is no longer negligible, and as a result, the theory presented in section 2.3 should be applied.

Analysis has shown that the viscosity is determined at high Ca-numbers and as a result, it should decrease with increasing air content, as can be seen in figure 7 (Feys et al., 2009b). The yield stress in case of SCC on the other hand is determined at low Ca-numbers for the air bubbles sizes measured (on the hardened concrete). Consequently, the yield stress should increase with increasing air content, which is also visible in figure 7 (Feys et al., 2009b).

As a result, the air content theory is capable of explaining both the decrease in viscosity and increase in yield stress. On the other hand, it is not applicable to mixture 17, as it does not predict any increasing sensitivity for segregation.

From a practical point of view, an increase in yield stress can lead to a decrease of filling ability of the SCC, resulting in the imperfect filling of a formwork.

5.3 Combination of effects

Both effects of structural breakdown and increasing air content act simultaneously on the concrete. According to both theories, the viscosity decreases, but depending on the initial fresh properties of the concrete, the yield stress after pumping can evolve in two ways, as observed in the experiments. In case of SCC with a rather high slump flow, the structural breakdown theory is more dominant and an increased danger for segregation is noticed. In case the initial slump flow is low, the air content theory is more dominant and the yield stress increases.

From the restricted amount of results, it is also observed that the magnitude of the effects increases with increasing pumping velocity. As a result, in order to minimize the effects, pumping should be performed at low velocities.

5.4 Mixture 14

Mixture 14 shows different results compared to the other mixtures because no increase in air content is observed. The specific reason for this behaviour can be the very high amount of SP applied. As this mixture contained less water than mixture 16, and approximately the same slump flow was targeted, it contained more than double the amount of SP applied in mixture 16. Possibly, this amount of SP increases the surface tension of the air bubbles in the concrete, making it more difficult to deform (as Γ increases in equation 2).

On the other hand, due to large problems during insertion of the concrete, the concrete age was quite elevated (150 min) at the beginning of the test. As a result, some effects of loss of workability can affect the measured results. When omitting these possibly affected results (Q4 in table 1), the evolution of the concrete obeys the structural breakdown theory.

6. CONCLUSIONS

The fresh properties of SCC are described by its rheological values: yield stress and plastic viscosity. The yield stress is the resistance to the initiation of flow, while the plastic viscosity is the resistance to a further acceleration of flow.

By means of full-scale pumping tests in quite long circuits, it is shown that the fresh properties are affected by pumping. A special testing procedure was developed in order to investigate these effects. From the full-scale pumping tests, it is observed that the pressure loss at a certain discharge decreases when a higher discharge is applied before. The rheometer results and the tests on fresh concrete confirm a decrease in plastic viscosity, but the yield stress can evolve in two different ways.

Two causes are found to influence the rheological properties of SCC during pumping: structural breakdown and an increase in air content. Due to structural breakdown, both yield stress and viscosity should decrease and the danger for segregation increases. According to the increase in air content, viscosity should decrease, but the yield stress must increase, which can lead to an improper filling of the formwork. Both effects appear to become more important with increasing pumping velocities.

ACKNOWLEDGEMENTS

The authors would like to thank the Research Foundation in Flanders (FWO) for the financial support of the project, and the technical staff of both the Magnel and Hydraulics Laboratory for the preparation and execution of the full-scale pumping tests.

REFERENCES

1. Chapdelaine F., 2007, Fundamental and practical study on the pumping of concrete, Ph-D-thesis (in French), Université Laval.
2. Feys D., 2009, Interactions between rheological properties and pumping of self-compacting concrete, Ph-D-thesis, Ghent University.
3. Feys D., Verhoeven R., De Schutter G., 2009a, Why is fresh self-compacting concrete shear thickening?, Cem. Conc. Res. 39, pp 510-523.
4. Feys D., Roussel N., Verhoeven R., De Schutter G., 2009b, Influence of the air content on the steady state rheological properties of fresh SCC, without air-entraining agents, Proc. of the 2nd intern. symp. on design, performance and use of SCC, Beijing, pp 287-295.
5. Kaplan D., 2001, Pumping of concretes, Ph-D-thesis (in French), Laboratoire Central des Ponts et Chaussées, Paris.
6. Roussel N., 2006, A thixotropy model for fresh fluid concretes: theory, validation and applications, Cem. Conc. Res. 36, pp 1797-1806.
7. Rust A.C., Manga M., 2002, Effect of bubble deformation on the viscosity of dilute suspensions, J. Non-Newt. Fluid Mech. 104, pp 53-63.
8. Tattersall G.H., Banfill P.F.G., 1983, The rheology of fresh concrete, Pitman, London.
9. Wallevik O.H., 2003a, Rheology – A scientific approach to develop self-compacting concrete, Proc. of the 3rd intern. symp. on SCC, Rejkjavik, pp 23-31.
10. Wallevik J.E., 2003b, Rheology of particle suspensions Fresh concrete, mortar and cement paste with various types of lignosulfonates, The Norwegian University of Science and Technology, Trondheim.
11. Wallevik J.E., 2009, Rheological properties of cement paste Thixotropic behaviour and structural breakdown, Cem. Conc. Res. 39, pp 14-29.