Similarities and Differences of Pumping Conventional and Self-Compacting Concrete

Dimitri Feys[1], Geert De Schutter[2], Ronny Verhoeven[3] and Kamal H. Khayat[1]

[1] Department of Civil Engineering, Université de Sherbrooke, Québec, Canada
[2] Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering, Ghent University, Belgium
[3] Hydraulics Laboratory, Department of Civil Engineering, Faculty of Engineering, Ghent University, Belgium

Abstract. In practice, self-compacting concrete (SCC) is considered as a simple extension of conventional vibrated concrete (CVC) when pumping is concerned. The same equipment, materials, pumping procedures and guidelines used for CVC are applied when pumping SCC. On the other hand, it has been clearly shown that the rheological properties and the mix design of SCC are different than CVC. Can the same pumping principles employed for CVC be applied for SCC? This paper compares the some published results of pumping of CVC with those for SCC. A first striking difference between pumping of CVC and SCC is the flow behaviour in the pipes. The flow of CVC is a plug, surrounded by a lubricating layer, while during the flow of SCC, part of the concrete volume itself is sheared inside the pipe. As a result, the importance of viscosity increases in case of SCC. Due to the low yield stress of SCC, the behaviour in bends is different, but quite complex to study. Due to the lower content of aggregate and better stability of SCC, as it is less prone to internal water migration, blocking is estimated to occur at lower frequency in case of SCC.

Introduction

Pumping of concrete is a worldwide applied casting method enabling fast and efficient concrete placement. For conventional vibrated concrete (CVC), the results of scientific investigations and practical guidelines can be easily found in literature [1-4], while for self-compacting concrete (SCC), the number of investigations published is quite restricted [5-7]. On the contrary, SCC is largely applied in the concrete industry and is often placed by means of pumping. In practice, it is assumed that pumping of SCC is similar to pumping of CVC, and that the same rules would apply. On the other hand, SCC is a different concrete with a different composition and rheological behaviour [7, 8]. Therefore, it is important to know if the rules for CVC would apply for SCC.

This paper compares the literature results for pumping of CVC with the results obtained during a research project on pumping of SCC. It will point out the main differences in mix design and rheological properties between the two concrete types and the consequences of these differences on the main parameters influencing the pumping pressure.

Experiments on SCC

Test setup

Pumping experiments on SCC were conducted with a truck-mounted piston pump, having two cylinders alternately pushing concrete inside the pipeline and pulling concrete from the reservoir of the pump. A powerful valve in the pump switches the connection between the pipes and the cylinders when the pushing cylinder is empty and the pulling cylinder is full. The output discharge rate of the pump could be varied over 10 different steps from the lowest step: 4-5 l/s (defined as step 1) to the highest step: 40 l/s (step 10). During the experiments, the maximum discharge rate was restricted to 19-20 l/s (step 5) for safety reasons.

Behind the pump, two different types of loop circuits were installed using steel pipes with an inner diameter of 106 mm: a short circuit with a length of approximately 25 m (Figure 1), and long circuits with lengths varying between 80 and 105 m. In both types of circuits, the pressure loss was measured in a straight horizontal section by means of two pressure sensors, located approximately 10 m from each other. As a back-up for the each pressure sensor, three strain gauges were attached to the outer wall of the pipe. As pipe deformation can be related to the occurring pressure [1], strain gauges were also attached to the pipe walls in other locations than the pressure sensors to monitor pressure evolution in the long circuits, including sections containing a bend.

As the theoretical volume of a pumping cylinder is 83.1 liter, the discharge rate was determined indirectly by measuring the time between two changes of the pumping valve, which corresponds to the contents of one pumping cylinder. This measuring method was verified by pumping the concrete present inside a full cylinder into a reservoir suspended with a load cell to a rolling bridge. By measuring the variations of the mass of the concrete discharged into the reservoir with time, the discharge rate was calculated. Both measurement methods were shown to deliver similar discharge rates.

Figure 1. Short pumping circuit (25 m).

Testing procedure

As the volume of concrete required for the pumping tests was 1.5 and 3.25 m^3 for the short and long circuits, respectively, the concrete was prepared in a ready-mix plant and delivered to the laboratory in a time span of approximately 45 min. After filling the pipe with concrete over 10 min for the short circuit, the first test could be started around 60 min following water-cement contact. For the long circuits, the quantity of priming mortar appeared to be insufficient to avoid blocking during the filling of the pipes and consequently, the first test was started at later concrete ages: between 1 and 2 hours. The tests on fresh concrete indicate that even at this age, the concrete still has self-compacting properties.

The testing procedure consisted of pumping the concrete at the five lowest available discharge rates, in a descending order (steps 5 to 1) and maintaining each discharge rate for five full strokes (Figure 2). In this way, pressure loss, measured as the pressure difference between the two pressure sensors divided by the separation distance, vs. discharge rate curve could be obtained in relatively short period (4 min). This procedure was repeated at 30-min intervals until the workability of the concrete decreased below the SCC level. Simultaneously to the pumping experiment, rheological properties of the SCC were determined using a Tattersall Mk-II rheometer [7, 9] in addition to standard characterization of SCC workability (slump flow, V-funnel and sieve stability in addition to unit weight and air content).

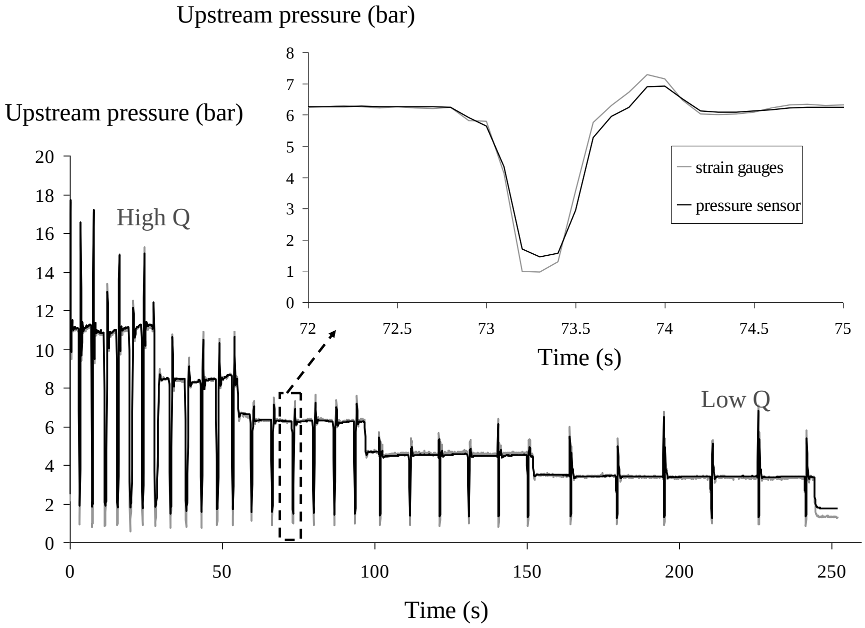

Figure 2. Upstream pressure variation with time, clearly indicating the five different discharge rate steps.

Concrete composition

In total, 19 different concrete mixtures were produced for the pumping tests. The mixture proportioning of these concretes are given in Table I. Most of the mixtures were prepared using ordinary high strength Portland cement (CEM I with 52.5 MPa cement strength at 28 days), limestone filler, natural sand, rounded river-bed gravel with maximal size of 16 mm and polycarboxyl-ether superplasticizer with a long workability retention. As can be seen in Table I, the mixture proportioning is based on the powder-type method for SCC mix design [8]. Four of the concrete mixtures were commercial products supplied by the ready-mix concrete producer. Mixtures SCC 14-17 were pumped in the long circuits, the others were used in the short circuit.

Table I. Concrete compositions.

Composition [kg/m^3]	SCC 0	SCC 1	SCC 2	SCC 3	SCC 4	SCC 5	SCC 6	SCC 7	SCC 8	CVC 1
Gravel 8/16	Commercial mixture	434	434	434	459	434	434	434	434	Commercial mixture
Gravel 2/8		263	263	263	278	263	263	263	263	
Sand 0/5		853	853	853	901	853	853	853	853	
CEM I 52.5 N		360	360	360	300	360	360	360	360	
Limestone Filler		239	239	239	200	239	239	239	239	
Water		165	165	165	165	165	165	165	165	
SP [l/m^3]		11	11	15.22	12.16	20.95	13.33	12.69	14.44	
Initial SF [mm]	740	640	720	690	710	710	720	650	680	190*

Composition [kg/m^3]	SCC 9	SCC 10	SCC 11	SCC 12	SCC 13	SCC 14	SCC 15	SCC 16	SCC 17
Gravel 8/16	410	434	410	434	434	434	Commercial mixture	434	Commercial mixture
Gravel 2/8	248	263	248	263	263	263		263	
Sand 0/5	805	853	805	853	853	853		853	
CEM I 52.5 N	400	360	400	360	360	360		360	
Limestone Filler	300	239	300	239	239	239		239	
Water	165	165	165	165	165	160		165	
SP [l/m^3]	18.15	11				21.9			
Initial SF [mm]	850	800	700	675	700	640	650	700	700

*slump

Comparison between CVC and SCC

Mix design and rheological properties

As stated in the previous sections, the mix design of SCC differs from CVC in order to enhance the flowability, reduce blocking due to accumulation of aggregates and avoid segregation. The amount of coarse aggregates in SCC is reduced and the viscosity of the concrete is increased by means of viscosity-modifying agents (VMA), or by increasing the amount of fine particles in the concrete, or by combining both. In this experimental project, the powder-type method was applied, by adding limestone filler to the concrete.

The rheological behaviour of fresh concrete is mostly described by means of the Bingham model (defining a yield stress and a plastic viscosity) [9-11], when transient behaviour, like thixotropy is not considered [11]. As generally known, SCC has a low yield stress, resulting in a high slump value [12]. The order of magnitude for the yield stress is between 10 and 100 Pa for SCC, while it can achieve several thousands of Pascals for CVC. For “pumpable” conventional vibrated concrete, the yield stress roughly varies between 100 and 1000 Pa [1]. The viscosity of SCC is increased by means of VMA or an additional amount of small particles to prevent segregation of the coarse aggregates. As a result, the viscosity of SCC is generally higher than the viscosity of CVC.

Behaviour law in pipes

The movement of concrete in pipes can be determined by two physical processes: flow or friction [1, 13]. In case friction is negligible, the deformation of concrete in pipes occurs according to the hydrodynamic laws, and as concrete has a high viscosity, the occurrence of turbulence in straight sections is quite rare. As a result, the flow is laminar, and rheological principals for dense suspensions can be applied.

The pressure gradient during pumping does not only push the concrete through the pipeline, but also tends to move the water among the granular skeleton [13]. In this case, the water content is no longer homogeneous along the conveying pipeline and in zones suffering a reduction in water, the stress is no longer transferred through the liquid, but by friction among aggregates. Browne and Bamforth examined both behaviour laws for the movement of concrete in pipes and concluded that the frictional behaviour causes a significantly higher pressure to pump the concrete, compared to the hydrodynamic behaviour [13]. Also in practice, “pumpable” CVC contains relatively large amount of fine particles to reduce friction, and stable concrete is less prone to friction than unstable mixtures.

As discussed in the previous section, special care is taken to avoid segregation in case of SCC, by adding VMA or more fine particles [8]. In theory, SCC should flow in the pipes according to hydrodynamic laws, which is confirmed by the conducted experiments. No blocking was observed during regime conditions (after insertion), even when a segregating concrete was fed into the pump (SCC 9 and 10). During the start-up of pumping, on the other hand, the experiments on the long circuits indicate a large amount of blockings due to a lack of fine particles at the concrete front, causing friction between coarse aggregate particles. The amount of fine particles at the concrete front decreases, as they stick to the pipe wall to lubricate the concrete and as they need to fill the space in the rubber seals installed in the connections between the pipes. Blocking during start-up was reported by Kaplan as the most frequent blocking occurrence [1] and can be prevented by inserting a priming mortar in the pipes before the pumping of concrete starts.

Flow in straight sections – velocity profile

In order to estimate the velocity profile of different types of concrete flowing through pipes, the theoretical framework for laminar flow in cylindrical pipes will be introduced, which is known as the Poiseuille formula in case of Newtonian liquids. The shear stress at the wall of the pipe is related to the pressure loss by equilibrium of forces (Eqn. (1)):

$$\tau_w = \Delta p \cdot R / 2 \tag{1}$$

where: τ_w = wall shear stress (Pa)
Δp = pressure loss per unit of length (Pa/m)
R = radius of the pipe (m)

The shear stress varies linearly with the pipe radius, from zero in the center, to the maximum value at the wall (τ_w). Incorporating the rheological behaviour law into the shear stress profile delivers the shear rate distribution, which can be integrated to obtain the velocity profile. The presence of a yield stress causes a zone with zero shear rate in the center, resulting in a constant velocity, also known as the plug. The larger the yield stress, the larger the plug radius and in the limit, no flow should occur if the wall shear stress is equal to or smaller than the yield stress of the concrete. As the yield stress of CVC is quite high, this would result in elevated pressure to start the flow of CVC. In order to facilitate its movement in pipes, concrete creates a water-cement layer of lower rheological properties near the wall [1-2]. As a result, the concrete can move much faster through the pipes and flow is observed even if the wall shear stress is lower than the yield stress of the bulk concrete.

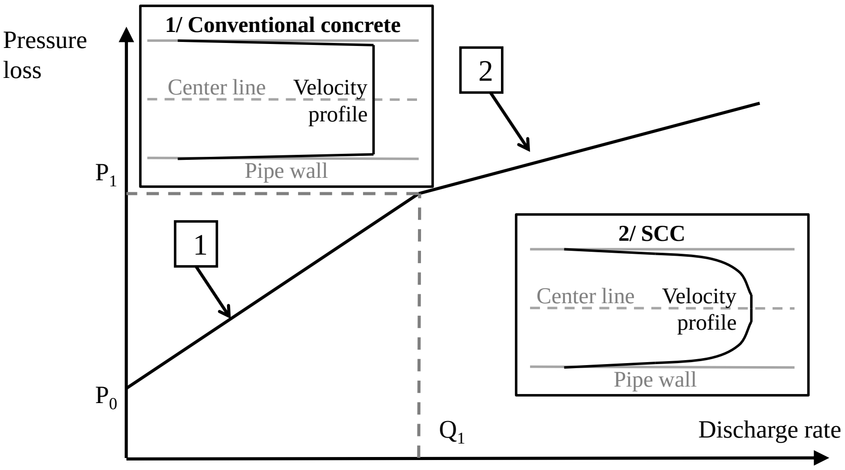

Figure 3. Distinction between pure plug flow with a lubrication layer (zone 1) and plug flow with a lubrication layer and partly sheared concrete (zone 2), based on pressure loss – discharge rate curve. (Q1, P1) represents the theoretical point where the wall shear stress equals the concrete yield stress. Figure after Kaplan [1].

Kaplan made a distinction between two different types of velocity profiles of the pressure loss – discharge rate curve, as can be seen in Figure 3 [1]. In zone 1, on the left side, the pumping parameters are only governed by the properties of the lubrication layer, as the wall shear stress is lower than the concrete yield stress. In zone 2, the flow parameters are governed by both the properties of the lubrication layer and the properties of the concrete. The velocity profile in zone 1 consists of a plug (constant velocity) and a large velocity gradient near the wall due to the lubrication layer [1, 2], while in zone 2, the velocity profile consists of a plug, a large velocity gradient near the wall and a smaller velocity gradient in between, because the concrete itself is also sheared [1, 7]. Conventional concrete has a rather high yield stress and in most cases is situated in zone 1, while SCC has a rather low yield stress, and is mostly situated in zone 2.

SCC also creates a lubrication layer near the wall during pumping, as the theoretical framework delivers significantly larger pressure losses at a certain discharge rate, compared to the experiments [7]. On the other hand, as the yield stress is low, a large part of the concrete is sheared, and a good relationship between the viscosity of the concrete and pressure loss can be established. This relationship is dependent on the discharge rate (Figure 4).

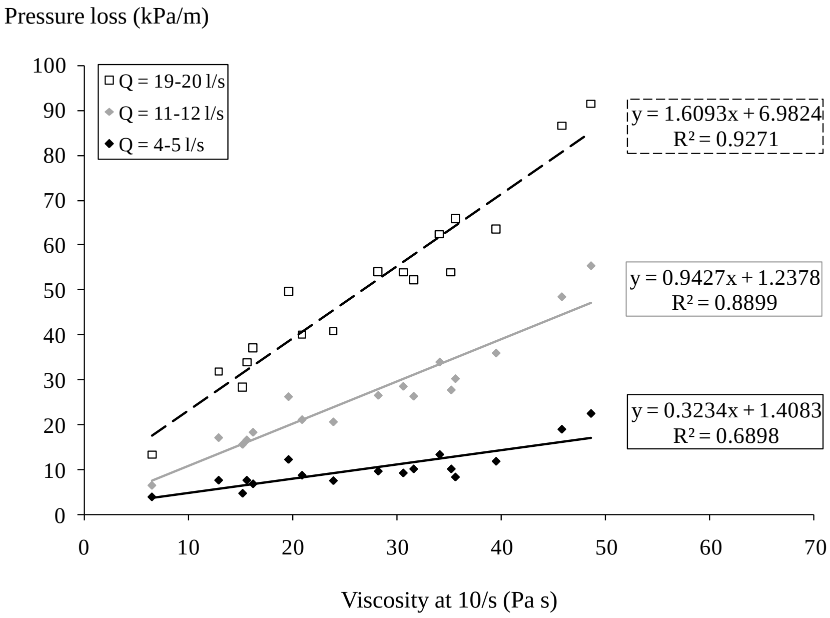

Figure 4. Variations of pressure loss with plastic viscosity of SCC determined at different discharge rates.

Note that these results are empirical and the relationship will change with varying discharge rate and pipe diameter. On the other hand, it is clearly shown that viscosity of SCC, rather than the yield stress, is the main factor influencing pressure loss. Such pressure loss corresponds to the required pumping pressure. Further research should be carried out to identify the relative importance of the lubrication layer for pumping SCC.

Pressure loss in bends

As in case for pure water, existing literature delivers non-conclusive results regarding pressure loss in bends of pipelines for CVC. For example, Kaplan [1] and Chapdelaine [2] did not observe any noticeable additional pressure losses in bends in during their field pumping experiments, while practical guides for pumping introduce the concept of equivalent length to account for the presence of bends in pumplines [3, 4]: e.g. one bend of 90° is equivalent to 3 m of straight pipes [4].

For SCC flowing in bends, an additional pressure loss was observed during the pumping experiments in the long circuits, which appears to be larger compared to CVC. It is important to note that the large scatter of the results prevents accurate conclusion on the level of increase in pressure loss in bends [7]. As the concrete flow needs to change direction across a bend, it is estimated that pressure loss in bends is influenced by a large number of parameters, including viscosity, inertia, coarse aggregate properties, bending radius and helicoidal flow velocity. As a result, further research is needed to capture these phenomena in details in order to develop guidelines and models that can take into account flow of SCC in bends.

Conclusions

By means of the results available in literature for CVC and experimental research project on pumping of SCC, comparison between pumping of CVC and SCC was made. The velocity profile for CVC flowing through pipes is composed of a lubrication layer with a large velocity gradient and a plug in which the velocity is constant. For SCC, the radius of the plug is much smaller than for CVC, and a smaller velocity gradient is present between the lubrication layer and the plug. As a result, a part of the concrete volume is also sheared in the pipes. The pumping parameters for CVC depend mainly on the properties of the lubrication layer, while for SCC, a good relationship between concrete viscosity and pressure loss was established. The flow in bends is complicated leading to non-conclusive results for both CVC and SCC. Further research is required to clarify the influencing factors.

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