Thixotropic Effects During Large-scale Concrete Pump Tests on Site

Geert De Schutter

Magnel Laboratory for Concrete Research, Ghent University, Belgium.

Abstract

During recent years, the fundamentals of pumping fresh concrete have been intensively studied worldwide. New insights have been gained concerning the important role of the lubrication layer near the surface pipe. The influence of rheological properties of the fresh concrete, like yield stress, viscosity, and shear thickening behavior, is now well understood, and can be fairly accurately modelled. One major challenge is found in the potential effect of thixotropy while pumping fresh concrete, especially in case the pumping operation is temporarily paused and resumed after a while. Due to thixotropic effects, restarting the pumping operation can be a very challenging task. This paper reports on a large-scale concrete pump test on a construction site, specifically focusing on the risk of thixotropy. Fresh concrete has been pumped in a horizontal closed-loop pumping pipe with a total length of 600 meter. In steady-state pumping conditions, the pumping operation was very successful, and in agreement with the expectations. However, the thixotropic effects, occurring during a short stop of the pumping operations, showed to provoke major problems while trying to resume pumping. The lessons-learnt helped to define a successful pumping procedure for this major construction site.

Keywords: Concrete, pumping, thixotropy, rheology.

1 INTRODUCTION

Pumping of fresh concrete is a commonly used technique to cast structural elements on site. With the introduction of new types of concrete, such as self-compacting concrete, new research insights have been obtained in the pumping behaviour of fresh concrete, explaining the important role of the lubrication layer near the pipe surface, the effect of internal shear in the concrete, and the occurrence of a plug zone in the centre of the pipe. A recent update on the basic understanding and remaining challenges of pumping of fresh concrete can be found in [1].

The in-regime pumping of fresh concrete seems well understood now, and pressure-discharge relations can be simulated in a reasonable way. Practical difficulties typically occur during the starting phase of the pumping process. In order to prepare the pipe surface and facilitate the formation of the lubrication layer, a cement mortar is typically pumped first. Afterwards, the concrete is entered into the pipes, and a lubrication layer is properly formed thanks to the presence of a thin paste layer on the pipe surface, and due to further shear-induced particle migration inside the concrete. Without a proper start-up procedure involving cement mortar, the risk of blocking inside the concrete pipe is very high.

Less known and less understood is the fact that blocking can also occur after a short stand-still of the pumping process (e.g. due to delay of a concrete truck), during the restarting phase. Short interruptions of the pumping process can lead to significant problems in resuming pumping operations because of internal structural build-up in the fresh concrete, also called thixotropy.The physical origin of thixotropic behavior is discussed in [2], but is beyond the scope of this paper. A pragmatic model to describe thixotropy is given in [3], and is reprinted in equations (1) and (2).

$$\tau = (1+\lambda)\tau_0 + \mu_p\dot{\gamma} \tag{1}$$

$$\frac{\partial\lambda}{\partial t} = \frac{1}{T} - \alpha\lambda\dot{\gamma} \tag{2}$$

In equation (1), λ is the flocculation state of the material, τ is the shear stress, τ_0 is the yield stress, μ_p is the plastic viscosity, and $\dot{\gamma}$ is the shear rate. The first term in the right hand side of equation (2) is the structuration rate, while the second term can be seen as the de-structuration rate. When the concrete is at rest, e.g. when the pumping operations are being paused, the evolution of the apparent yield stress as a function of time t is given by equation (3).

$$\tau_0(t) = (1+\lambda)\tau_0 = \tau_0\left(1+\frac{t}{T}\right) = \tau_0 + A_{thix}t \tag{3}$$

The parameter A_{thix}, also equal to τ_0/T, is the structuration rate, expressed in Pa/s. By means of this thixotropy model, some experimentally obtained results in a large-scale pump test on a construction site will be analysed to further illustrate the effect of thixotropy on pumping operations.

2 LARGE-SCALE PUMPING CIRCUIT

For the construction of a railway tunnel in Belgium, concrete needed to be pumped over a distance of about 1 km, into the tunnel. Before the start of the real pumping operations, a large-scale trial pump test was set up on the construction site. A closed-loop horizontal pumping circuit was installed with a total length of 600 m. The setup is illustrated in figure 1, showing the powerful concrete pump, the sequence of concrete pipes, and the final pipe returning the fresh concrete to the pump, closing the loop.

A powerful piston pump was used, with a capacity of about 350 bar. During each single stroke of the pump, a concrete volume of 0.063 m³ was pushed into the pumping pipe. The steel pipes had a diameter of 125 mm, and have been prepared by firstly pumping a specially prepared cement mortar. Afterwards, the concrete was introduced into the pump and the pipes, and during a couple of minutes, the concrete was pumped around, and some measurements were performed, including conventional workability tests on the pumped concrete (see further).

The main goal of the large-scale pump test however, was to test the effect of a stand-still of the fresh concrete during 15 to 20 minutes, the maximum waiting time which was estimated to occur in the real production in case of delay of a truck mixer. So, after the first cycle of steady-state pumping, the pumping operation was halted, and the concrete remained at rest within the pipes. After the prescribed waiting time, the pumping operation was to be resumed, monitoring required pump pressures.

Figure 1: Layout of the closed-loop pumping circuit with a total length of 600 m

3 CONCRETE

A conventional vibrated concrete was used in the pump test, with a composition as given in table 1. Blast furnace slag cement of European type CEM III/A 42.5 N LA has been used. The strength class of the concrete is C30/37 according to the European standard EN 206.

Table 1: Concrete mix design

Material	**Amount (kg/m³)**
Cement CEM III/A 42.5 N LA	365
Fly ash	90
Limestone aggregate 2/6	195
Granite aggregate 2/22	765
Coarse sand 0/4	496
Fine sand 0/1	210
Plasticizer (naphtalene-based)	6
Retarder	0.5
Water	195

On arrival at the construction site, conventional workability measurements have been performed on the fresh concrete. The slump of the concrete was equal to 220 mm (Figure 2), and the flow was equal to 640 mm (Figure 3). It is important to mention that the concrete was retarded in order to avoid the influence of workability loss within the duration of the pump trials.

Figure 2: Slump measurement on fresh concrete at construction site

Figure 3: Flow measurement on fresh concrete at construction site

4 PUMP TEST RESULTS

After preparation of the pumping pipes with a cement mortar consisting per m^3 of 800 kg CEM III/A 43.5 N LA, 150 kg fly ash, 822 kg fine sand 0/1 and 335 kg water, the fresh concrete with composition given in table 1 was introduced into the pump and the pipes. The concrete was then pumped in the closed-loop during about 2 minutes, having 120 pump strokes. This means that the entire concrete volume of about 7.5 m^3 present in the pumping pipes made about one loop. At one stroke per second, the discharge rate was 63 l/s, or about 227 m^3/h. The required pumping pressure in steady-state regime was 220 bar in the pump. The real concrete pressure in the pipe was not measured directly, but according to previous experiences of the pump operators, the concrete pressure at the inlet of the pipe is estimated to be about 60% of the pump pressure, which means about 135 bar.

After one full pumping cycle, the workability of the concrete has been measured again, resulting in a slump value equal to 260 mm and a flow equal to 670 mm. This means that the concrete coming out of the pumping pipe showed a slight increase in workability. This could be explained by some intermixing with the cement mortar previously introduced into the pumping pipes in order to prepare the pipe surface. However, other effects could also occur, e.g. linked to the role of air [4]. Temperature effects can also intervene. The temperature of the concrete after one cycle of pumping increased to 26°C (coming from about 20°C on arrival on site) (Figure 4).

Figure 4: Temperature measurement on fresh concrete at construction site

After a second full cycle of pumping, with steady-state pump pressures now equalling 235 bar (estimated concrete pressure at inlet equalling about 140 bar), the concrete temperature increased to 27°C, while the slump flow value decreased to 220 mm from 570 mm.

At this stage, the pumping was paused for 20 minutes, simulating a delay in concrete delivery. After 20 minutes, the pumping pressures were increased again in order to resume pumping operation. At the maximum pump pressure capacity of 350 bar, it showed not possible to bring the fresh concrete in the pumping pipes into motion again. At this moment the estimated concrete pressure at the inlet of the pipes was about 210 bar, which was about 50% higher than the corresponding pressure in steady-state pumping conditions. Attempts to increase the applied pressure by circumventing the safety settings of the pump, assisted by the pump producer present on site, unfortunately did not help. Finally, the pumping pipes had to be dismounted for proper cleaning, and no further pumping cycles could be performed.

5 DISCUSSION

As retarder was added to the concrete, avoiding workability loss due to hydration during the pump test, the fact that the pumping operation could not be resumed after a pause of 20 minutes is mainly due to the thixotropic behaviour of the fresh concrete. Due to internal clustering and structure formation, the fresh concrete becomes stiffer, and shows a larger resistance against flow. Considering the fresh concrete as a homogeneous material in a cylindrical pumping pipe with diameter R, it can be shown that the shear stress τ_w at the pipe wall can be calculated by means of equation (4), as explained in [5].

$$\tau_w = \frac{\Delta p_{tot}}{L} \cdot \frac{R}{2} \tag{4}$$

In this equation, Δp_{tot} is the total pressure loss over the length L of the pipe with radius R. With the experimentally obtained pressure results mentioned in previous section, it can be calculated in this way that the shear stress at the pipe wall, having a total pressure loss of 210 bar over a length of 600 m, was equal to about 1100 Pa. Indicatively, it can thus be concluded by applying equation (4) that the apparent yield stress of the concrete at that moment, at the end of the 20 minutes waiting period, was at least equal to 1100 Pa.

During the steady-state pumping cycle preceding the 20 minutes waiting period, the total pressure loss was equal to 140 bar, which would indicate a yield stress of about 730 Pa (assuming that the yield stress in these flowing conditions could be estimated by the same conditions as in equation (4), neglecting the non-homogenous situation caused by the existence of a lubrication layer during active flow, which is questionable but acceptable in an indicative way).

Applying equation (3), and considering an increase in apparent yield stress from 730 Pa to 1100 Pa in 20 minutes (1200 seconds), it can be estimated that A_{thix} in this case was equal to about 0.3 Pa/s. While for reasons of formwork pressure reduction in freshly cast concrete walls a significant structuration rate A_{thix} is desirable, during pumping operations it can mean a significant problem and risk.

As only one pump test was performed (because of limited budget), the obtained values can only be considered as indicative. Nevertheless, the obtained results illustrate the potential order of magnitude of the thixotropic effects while pumping.

6 ERC ADVANCED GRANT PROJECT 'SMARTCAST'

As illustrated in this large-scale pumping test, short interruptions of the pumping process can lead to major difficulties in resuming pumping operations due to the sometimes tremendous effect of internal structural build-up or thixotropy. During a pause in the pumping operations, current practices do not allow for the active control of the concrete rheology. The pumping operator can only passively consider the evolution of the rheological properties of the cementitious material, in steady-state conditions or in rest, and has no means to adjust the material properties.

A potential solution to overcome this problem is currently studied in the ERC Advanced Grant Project 'SmartCast'[6], which aims to introduce a ground-breaking approach by developing an innovative concrete mix design containing responsive polymer admixtures interacting with applied electromagnetic fields, enabling the active rheology control (ARC) of the fresh concrete while being placed, and the active stiffening control (ASC) as soon as the concrete is in final position in the formwork. These active control features would bring a relevant solution for contradicting requirements e.g. related to the structuration rate A_{thix} as shown with the experiment described in this paper. Active control would limit the structuration while placing the concrete, and increase the structuration rate after casting, all of this with the same concrete mixture.

7 CONCLUSIONS

By performing a large-scale closed-loop pumping test on site, with a total pipe length of 600 m, some relevant conclusions can be summarized:

It was shown that short interruptions of the pumping process (e.g. due to the delay of a concrete truck) can lead to major difficulties in resuming pumping operations due to the effect of internal structural build-up or thixotropy. As the tested concrete was retarded, workability loss due to hydration could be excluded as significant factor.

Requirements limiting the structuration rate of the fresh concrete, in order to limit the risk of blocking after pausing and facilitating the restart of pumping operations, are contradictory to requirements in view of obtaining fast reductions in formwork pressures.

Active rheology control (ARC) and active stiffening control (ASC) of fresh concrete, as currently studied within the ERC Advanced Grant Project 'SmartCast', would make concrete pumping (and formwork casting) safer and more reliable.

8 ACKNOWLEDGEMENTS

The financial support of the European Research Council (ERC), as provided through the Advanced Grant Project 'SmartCast' (2016-2021) awarded to the author of this paper, is gratefully acknowledged.

9 REFERENCES

[1] De Schutter, G. and Feys, D., 'Pumping of Fresh Concrete: Insights and Challenges', RILEM Technical Letters (2016) 1, 76 – 81, DOI: http://dx.doi.org/10.21809/rilemtechlett.2016.15.

[2] Roussel, N., 'Understanding the rheology of concrete', Woodhead Publishing Limited, 2012, ISBN 978-0-85709-028-7.

[3] Roussel, N., 'A thixotropy model for fresh fluid concretes: theory, validation and applications', Cement and Concrete Research (2006) 36, 1797-1806.

[4] Feys, D., De Schutter, G., Khayat, K.,Verhoeven, R., 'Changes in Rheology of Self-Consolidating Concrete Induced by Pumping', Materials and Structures (2016) 49, 2016, 4657–4677, DOI 10.1617/s11527-016-0815-7.

[5] Feys, D., 'Interactions between rheological properties and pumping of self-compacting concrete', PhD thesis, Magnel Laboratory for Concrete Research, Ghent University, Belgium, 2009.

[6] De Schutter, G., "Smart casting of concrete structures by active control of rheology, Smartcast," ERC Advanced Grant Project, European Research Council, 2016-2021.