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# Influence of the viscosity of self-compacting concrete and the presence of rebars on the formwork pressure while filling bottom-up

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A B S T R A C T

Self-compacting concrete (SCC) enables new casting techniques, filling formworks by pumping bottom-up. However, fundamental questions remain concerning the formwork pressure when following this advanced filling procedure. A new series of formwork filling tests, with SCC being pumped from the base of the formwork, have been performed in 2012 at the Magnel Laboratory for Concrete Research of the Ghent University (MLCR). Numerical simulations of these formwork filling tests have also been carried out for validation with the experiments. For the filling process of eight casts in total, the influence of several filling parameters on the resulting formwork pressures were tested, like the casting speed, the presence of steel rebars (leading to a reduction of the flow section inside a formwork) and the rheology of the SCC. The formwork pressures were measured at three different positions on the formwork wall with accurate electronic pressure sensors. These measured formwork pressures were finally compared with the computed formwork pressures. Both the experiments and the simulations performed in this study showed a very good agreement and they revealed that the formwork pressures during the filling tests were higher than the hydrostatic pressure for SCC pumped from the base of the formworks. This was due to the additional occurring hydraulic losses. In our experiments, these additional flow losses represented 7% up to 16% of the total wall pressure for the performed filling tests with steel rebars, depending on the viscosity of the SCC and the casting speed. An analytical calculation model for the formwork pressure has been derived and validated, using the experimental measurements and the numerical simulations of the filling tests performed at the MLCR. Finally, the quality of the cast concrete, investigated through a visual inspection of a series of drilled concrete samples taken at several relevant locations of the casts, revealed to be excellent considering the high casting speeds.



## Research significance

Most of the available codes and guidelines for predicting the formwork pressure have been developed for casting processes with conventional vibrated concrete (CVC) [18–22]. Although the DIN 18218 standard [19] gives some design guidelines for use with SCC, these codes and guidelines are generally not suited for casting with SCC when pumped from the base at high casting speed (>7 m/h) [2,23,24]. CVC is traditionally cast from the top of the formwork in several layers, which are individually vibrated in order to remove the entrapped air as much as possible and to ensure good compaction around the steel rebars. As such, the casting speeds are rather low. The base filling technique with SCC, which is presented in this article, allows for much faster casting speeds with still good compaction. Although the formwork pressures are higher with base filling compared to top filling, the filling times can be significantly reduced. For the precast industry, this could mean a more cost effective manufacturing process at a higher production rate. The analytical model for calculating the formwork pressure, which has been derived in the present study, allows to quickly estimate the maximum occurring formwork pressure during a base filling casting process.

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## 1. Introduction

Traditionally, the fresh concrete is pumped through flexible ducts from the mixing truck into a formwork. Most of the time, the fresh concrete is poured inside the formwork from the top. When conventional vibrated concrete (CVC) is used, the casting process is interrupted several times in order to remove the entrapped air, using vibration rods. When self-compacting concrete (SCC) is used, there is no need to vibrate the fresh concrete because it is much more fluid than CVC and it fills the formwork under its own weight. This is why SCC is called "*self-compacting*".

Unlike the conventional filling of formworks from the top, we started to study the base filling process with SCC through a series of formwork filling tests being performed in 2010 at the Magnel Laboratory for Concrete Research (MLCR) of the Ghent University. This study was reported in a previous article [1]. Two columns and two walls were cast. The SCC was pumped bottom-up inside the formworks, and during the casting process the formwork wall pressures were recorded with pressure measurement devices. These pressure measurement devices were designed at the Laboratory for Hydraulics of the Ghent University. The design consisted of a manometer mounted on an intermediate water chamber, which was sealed with a rubber membrane and flush mounted on the formwork wall. However, this design needed further improvements. These formwork filling tests were also modelled numerically. The measured formwork wall pressures were compared with the simulated wall pressures. A prediction model for the determination of the formwork pressures when filling bottom-up was derived, based on the Bernoulli equation. The validity of this model was fully confirmed by the simulations, but only partially confirmed by the measurements due to measuring artefacts. Finally, thixotropy did not influence the formwork pressure, because of the relatively short filling times and the SCC being constantly sheared during the whole filling process.

In order to further expand our knowledge regarding the base filling process with SCC, new formwork filling tests were performed in 2012, also at the MLCR of the Ghent University in Belgium. The objectives for these new formwork filling tests were [1]:

- To test other pressure measurement devices.
- To study the influence of the rheology and more especially the apparent viscosity of the SCC on the formwork pressures.
- To study the influence of the casting speed on the formwork pressures.
- To study the influence of the presence of steel rebars on the formwork pressures.
- To study segregation of the SCC while pumping bottom-up.
- To consolidate the theory on formwork pressure development presented in a previous article [1].
- And last but not least, to fine tune the numerical models for these formwork filling processes.

Our motivation for choosing these objectives was twofold:

- Analysing the effect of the parameters which are commonly known to influence pressure and pressure losses in hydraulic processes, being the viscosity of a fluid, the local speed of a fluid and the flow cross section or the geometry of the flow domain.
- Assessing the impact of a high casting speed on the resulting cast quality.

The following Sections describes in detail these new base filling tests with SCC, as well as the related numerical simulations.

## 2. Physical testing – full-scale formwork filling tests

This section of the article describes the set-up, the instrumentation and the methodology followed during the eight full-scale formwork filling tests that have been performed at the MLCR. During these tests, eight columns were cast. The set-up of the formwork filling tests is shown in Fig. 1. The filling tests were performed for practical reasons on two separate days, with an interval of one week between them.

Table 1 shows the casting conditions for these filling tests. As already mentioned in the introduction, the influence of several casting parameters on the base filling process with SCC was studied. Two powder type SCC mixtures were selected for these filling tests with largely differing rheological properties. The composition of the SCC mixtures are presented a little further in this section, whereas the rheological properties of these SCC mixtures are summarised in Section 3.6.

The dimensions of the eight columns are identical. The columns have a height of 4 m, a depth and a width of 0.3 m. The inlet of the columns is positioned at 0.6 m above the ground. This inlet position was selected in order to easily mount the pressure measurement devices located at the base of the columns, and also to be able to put a basket underneath the inlet to collect the fresh SCC when disconnecting the supply duct (see Fig. 3). The rebar configuration consisted of four vertical bars with a diameter of 16 mm, which were connected with transverse reinforcement bars with a diameter of 6 mm. Fig. 2 shows the rebar configuration of the columns as well as the overall dimensions.

A Putzmeister concrete piston pump of type P 715 TD is used in all the filling tests for pumping the SCC inside the formworks. For these base filling processes, a mechanical shut-off valve has been designed at the MLCR, which is shown in Fig. 3.

While the formworks were filled, the SCC discharge rate was measured at the concrete pump. The discharge rate was also obtained by dividing the total volume of the formwork by the time needed to fill the cast. Table 1 summarizes the discharge rates as well as the resulting casting speeds for the eight columns. Column 4 was only filled up to a height of 3.5 m due to cracks appearing in the formwork front wall just above the inlet.

The time evolution of the formwork pressure during the filling of the columns was also recorded at three different positions: at the base of the formwork, at 1 m from the base and at 2 m from the base. Fig. 4 shows the locations of the pressure measurements for the columns. Figs. 5 and 6 show the two types of electronic pressure sensors that were used for measuring and monitoring the formwork wall pressures during the column casting processes. These pressure measurement devices were provided by the Belgian Building Research Institute (BBRI), as used in their previous research program [2]. The pressure sensors were calibrated with a very accurate hydraulic calibration unit. The pressure sensors of type 1 were mounted at the base of the columns, whereas the pressure sensors of type 2 were flush mounted on the walls of the formworks at 1 m and 2 m above the base.

As already mentioned, the formwork filling tests were performed with two SCC mixtures (see Table 1) on two separate days. A ready-mix company supplied both SCC's. A low viscosity SCC was used for the filling tests on the first day, while a high viscosity SCC was used for the casting tests on the second day. Table 2 lists the selected types and the amounts of the ingredients of both SCC mixtures.

The rheology of the SCC mixtures was measured with a BML Contec 5 rheometer. The standard fresh SCC tests (slump flow, V-funnel, L-box, sieve stability, air content) and the rheometer measurements were performed with the low viscosity SCC at three different moments during the filling tests: