THEORETICAL AND PRACTICAL INVESTIGATIONS ON SCC FORMWORK

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Abstract

Pressure forces that act on a formwork during casting of a SCC element are still subject of discussion among contractors and structural engineers. The differences in rheological behaviour between SCC and ordinary concrete turns out to be sufficient to mobilize different (hydrostatic) pressure forces. The consequence of this is that formwork, which is designed for ordinary concrete, does not satisfy when using SCC. This issue is the main subject of a research project [1] currently running at Delft University of Technology in corporation with NRG and BAM/DMC. With this project it is tried to uncover the theoretical as well as the practical issues of formwork used for SCC elements. With the software FLUENT[1], numerical simulations are conducted for a Funnel test and a full-scale wall. Experimental verification data is achieved from tests (BLM-viscometer and Rheolab MC1) conducted at the Stevin II lab of Delft University of Technology. From the numerical simulations and laboratory research, the pressure development of SCC during casting is examined. Results are compared with experimental data achieved from site measurements.

In the paper, an overview of the numerical and experimental results achieved from this research project will be provided. Emphasis will be on the formwork pressure as well as on the flow behaviour of SCC during casting.

1. INTRODUCTION

Today, the use of SCC has found its way in a wide range of applications in the prefabrication industry in the Netherlands, driven by the extremely good performance and substantially improved circumstances for workers at the production plants. The application of SCC on the building side however, is still lacking. Due to the fact that the mixture composition of SCC is very sensitive to small changes and, besides that, the mixture is also sensitive to changes of the environmental conditions. Another point is the fact that the

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[1] FLUENT is a commercial CFD software. CFD = Computational Fluid Dynamics.

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knowledge and understanding about the pressure build up inside the formwork is still missing. In this paper, results will be presented of an extended research project (MSc-thesis [1]) on the development of the formwork pressure of SCC elements. The experimental part of the project is conducted at Delft University of Technology and the numerical part of the research has been conducted at NRG in Petten in The Netherlands. This numerical research was based on the simulation of the Funnel test and on the simulation of a full-scale wall, representing a field test. For full-scale wall element, the actual formwork pressures have been measured in the field as well [1]. For the simulations, a CFD model was made while using FLUENT software. The main goals of the research were to investigate the possibility of modeling concrete flow using CFD and to examine how SCC can be cast under controlled formwork pressures.

2. FORMWORK PRESSURE

The Formwork pressure caused by SCC mixtures is often higher than the pressure build-up in conventional concretes. Several reasons are expected to have influence on this phenomenon such as the exceptional viscosity of SCC and a relatively high dosage of additives. It causes the hydration process to start later, resulting in an extension of the semi-fluid dormant stage. The codes and standards which are currently available do not offer any opportunity to calculate the expected formwork pressure of SCC since mixtures that fall within the highly fluid consistency classes are not well defined [4]. The CUR recommendation 93 [5] recommends to assume a hydrostatic pressure whenever the maximum formwork pressure is calculated for SCC mixtures, according to:

$$P = \rho \cdot g \cdot h \tag{1}$$

However, practice has learned that this is a very conservative approach. Site measurements [1,2,3] have shown a strong deviation of the actual formwork pressure relative to the ideal hydrostatic pressure (see Figure 1). From these site measurements, it turned out that the pressures almost never behave hydrostatically. This can be attributed to the fact that SCC has thixotropic properties. It means that at rest, internal colloidal attraction forces develop that strengthen the mix in such a way that the pressure forces remain unchanged or even reduce.

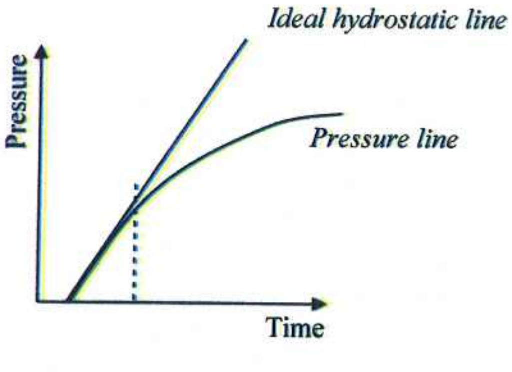

Figure 1: Schematic representation of the Ideal hydrostatic and realistic pressure line.

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3. FUNNEL TESTS

In order to evaluate the potential of CFD to simulate the flow behaviour of SCC, it was decided that, before simulating a full-scale wall, to start the research project with a model of the Funnel test. Part of this Funnel model was to evaluate whether it is possible to simulate the Bingham fluid [6] with the CFD software. Experimental verification tests were conducted at the Stevin laboratory of the Delft University of Technology. The tested mixtures consisted of bentonite-cement (4%) and cement-based mixtures. For these tests use is made of the small Funnel (see Figure 2). In order to save computation time, the left side of the Funnel has been modelled only. The mesh of this model is generated with the software GAMBIT. The model includes the triangular filling box, the flow outlet, the flow itself and the storage unit. At the top side of the model, the atmospheric pressure conditions were imposed and the SCC was considered to experience free flow conditions while leaving the triangular filling box. For the walls of the filling triangle a *no-slip* wall behavior has been assumed.

The rheological parameters of these cement-based mixtures were measured in the laboratory, using a MC 1 Rheolab rheology apparatus. The parameters were used to define the properties of the SCC (fluid) in the FLUENT software. It was found that the Funnel time could be determined very accurately from the velocity plot of measuring point 9 in the mouth of the Funnel. This point represents the location where the free falling SCC intersects with the surface of the SCC inside the storage unit. A representative plot of the velocity is provided in Figure 2 (right). The four characteristic stages (a t/m d) of the Funnel velocity, i.e the points mentioned in Figure 2, are provided in Figure 3 by means of contour plots.

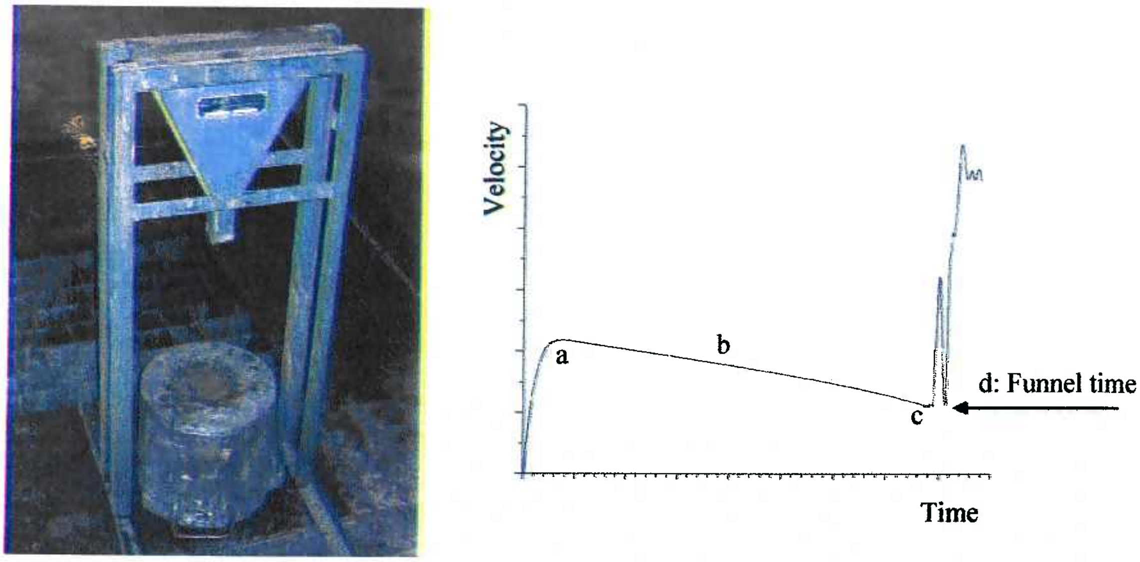

Figure 2: Left: Funnel used for tests; Right, Representative velocity plot at point 9.

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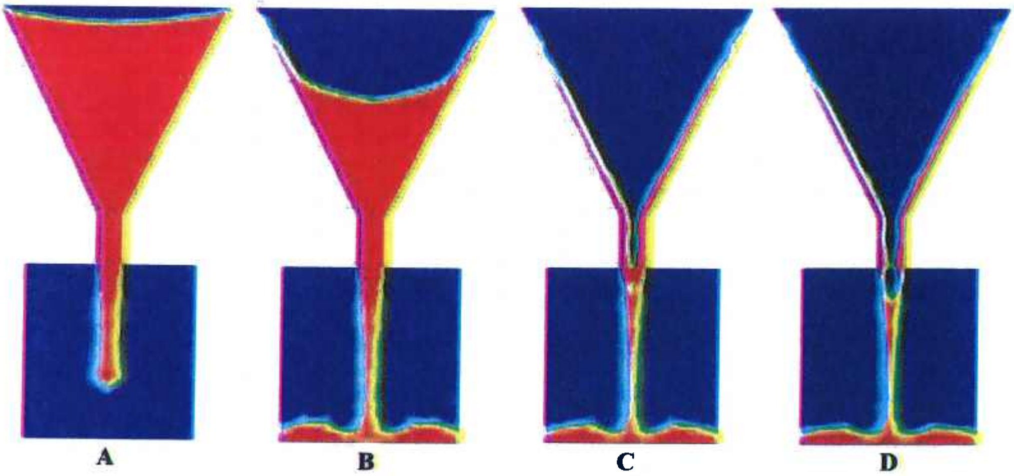

Figure 3: Contour plots of the different stages during a Funnel test.

The results from the simulations are compared with the results achieved from the Funnel tests [1]. In Figure 4, experimental and numerical results are provided for various water-cement ratios. The results show that good agreement could be reached for the Funnel times. The results show similar tendency for both the bentonite-cement and cement mixtures. With respect to the cement mixture, the large deviation for a water-cement ratio of 0.41 is due to the fact that the Funnel blocked during the measurement. The CFD model could not predict this blocking effect in the Funnel test. In general, the differences between the measured and simulated Funnel time can be partly explained by the uncertainty of the flow behavior of the concrete near the Funnel wall. In the CFD model, the no-slip wall boundary behavior has been assumed for the bentonite-cement mixture as well as for the cement mixture itself. The over prediction of the Funnel time by CFD for the bentonite-cement mixture might be caused by some slip of the cement near the Funnel wall. The complicated rheological behavior [6] of concrete and the uncertainties in the experimental conditions and data will also explain the differences between predicted and measured data, e.g. for the cement mixture.

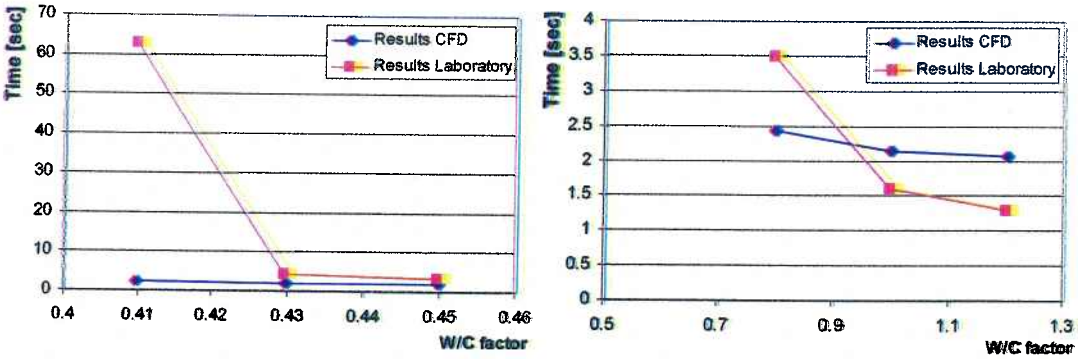

Figure 4: Funnel test results; Left: cement-mixture; Right:Bentonite-cement mixture (4%).

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4. FULL-SCALE WALL

As part of this research project formwork pressures were measured at four full-scale walls, cast in SCC. The walls where 6 meters in height and 6 meters wide with a thickness varying between 310 to 170 cm. If hydrostatic pressure would develop in the SCC, the bottom part of the formwork would be loaded by a pressure of 2220 kg/m^3 * 9.81 m/s^2 * 6 m = 133 kN/m^2. It was interesting to see that in all 4 measurements a sort of ideal pressure line could be identified that would develop under ideal circumstances. This pressure line follows the hydrostatic line for roughly the first hour after casting and then starts do deviate from it (Figure 1). For three pressure sensors positioned at the bottom of the formwork, this ideal line could clearly be observed. This holds until the surface of the SCC reaches the bottom side of the recess, at a casting height of 3.70 meter. At this point, whenever the concrete is cast through the opening at the right hand side of the formwork only, the SCC starts to flow underneath the recess to fill-up the space at the other side of the recess (see Figure 6). This causes a certain part of the concrete underneath the recess in a flowing motion, which prevents this part of the concrete from setting. The concrete in this part, therefore, shows a delay in deviating from the pressure line, or even worse, tends to return to the hydrostatic pressure line again (see Figure 5, right). This phenomenon can be seen from the figure until the moment where the recess collapsed and the SCC started to fill-up this space as well. This incident immediately caused a drop of the concrete level and, therefore, the pressure line has been affected as well.

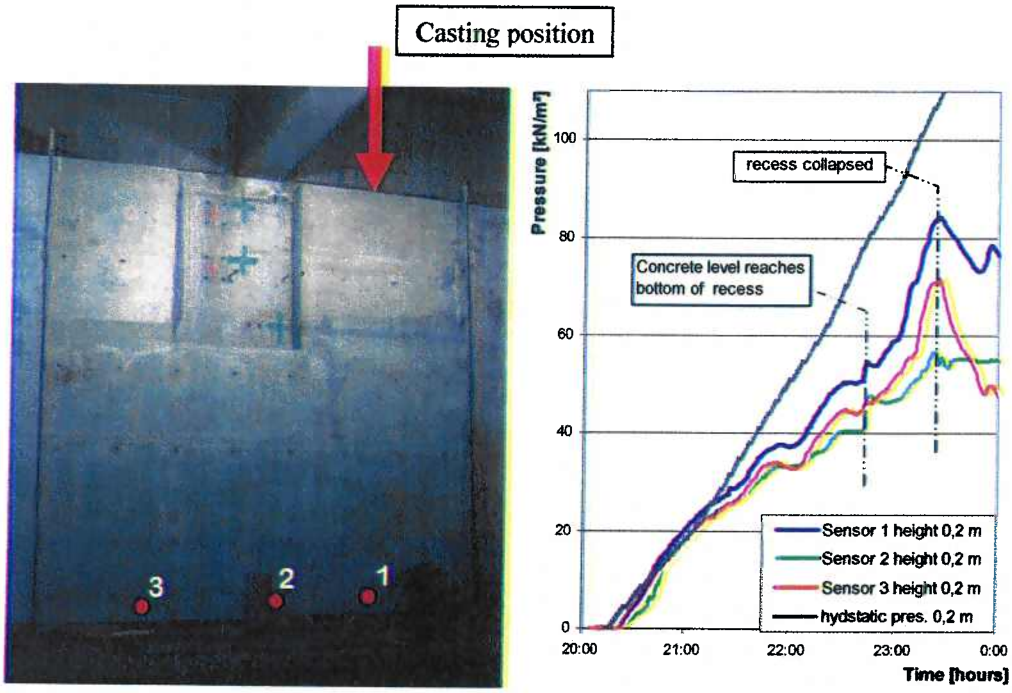

Figure 5: Left: Full-scale SSC wall (with sensor points); Right: Pressure lines during casting.

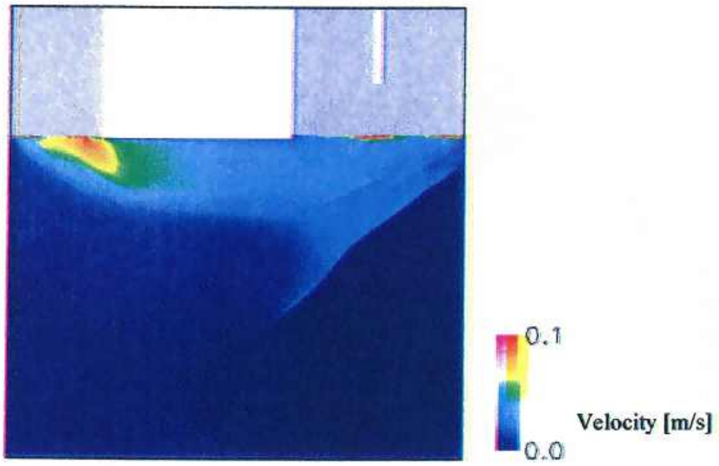

Figure 6: Numerical simulation of the flow field inside SCC during casting.

A 2D numerical model was made for the full-scale wall as shown in Figure 6. In this model, casting situations were simulated that associated with experiences observed at the site. One of these situations was the flowing of the SCC underneath the recess. The rheological parameters were obtained from rheology measurements with a BML viscometer done on the mixture that was used on the building site. The rheological behaviour used in the FLUENT software was modelled with the Bingham model. The initial situation is the situation where the SCC has reached the bottom of the recess and that the level on the right side is set 10 centimeters higher than the level on the left side. Shown is the result after 4.5 seconds and it can be seen that the area of which is affected by the flow of SCC covers more than half the depth and is spread over the total width of the formwork.

5. CONCLUSIONS

The present study demonstrates the capability of CFD software to predict the flow behavior of SCC. Funnel tests can be simulated well, considering the complicated rheological behavior of concrete and the uncertainties in the experimental conditions and data. The coupling between the flow behavior of concrete during casting and the development of the formwork pressure can be predicted by CFD modeling.

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