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Optimization of Rheological Properties of Self-Consolidating Concrete By Means Of Numerical Simulations, To Avoid Formwork Filling Problems in Presence of Reinforcement Bars

by

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16. Abstract

The influence of the rebar configuration on the occurrence of dead zones (= zero velocity) during flow of Self-Consolidating Concrete in formworks has been investigated by single fluid numerical simulations. The main findings showed that for small inter-rebar spacing, the shear stress in the concrete cover becomes very low. The rebars act as virtual walls, concentrating the SCC flow between them. Once the concrete cover is thus filled, the SCC remains stationary and can thus induce entrapment of air or a cold joint between the stationary concrete in the cover and the moving concrete in the center of the formwork. The numerical simulations have revealed that the SCC must be close to self-levelling to avoid the dead zones in case of a dense reinforcement grid. Increasing the spacing between the rebars and, to a minor extent, increasing the concrete cover allow for SCC with higher yield stresses, and thus lower viscosities to be employed, while avoiding the occurrence of the dead zones.

17. Key Words

Self-Consolidating Concrete, rheology, formwork, numerical simulations, reinforcement, flow, dead zone

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Optimization of rheological properties of Self-Consolidating Concrete by means of numerical simulations, to avoid formwork filling problems in presence of reinforcement bars

Final Report

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1. Introduction

In this project, the flow of Self-Consolidating Concrete (SCC) in formworks was simulated using COMSOL Multiphysics® to study the effect of the reinforcement rebar configuration on the flow pattern as well as finding critical rheological properties for adequate formwork filling.

Since SCC is a relatively new type of concrete which does not require any energy for consolidation [1], the flow pattern of SCC in the formwork can significantly influence the mechanical properties of concrete [2]. Especially, the occurrence of dead zones during formwork filling can entrap air and can induce lower mechanical properties and durability of the final structural elements. [3]. Dead zones also increase the risk of casting joints or cold joints, reducing the bond strength between the concrete layers [2].

Instead of performing large-scale experiments with large quantities of concrete, the flow in formworks can also be predicted by means of numerical, single fluid simulations, in which the concrete is assumed to be a fluid without particles. However, numerical simulations that take into consideration the influence of reinforcement on local patterns in SCC flow have not been reported extensively. Preliminary simulations have shown that a vertical bar creates additional zones with very low and very high shear rates, compared to the flow in non-reinforced elements [4].

The SCC is modeled as a single phase yield-stress fluid in a rectilinear channel with cylindrical objects. For the influence of the reinforcement configuration, four different rebar configurations were chosen in terms of concrete cover (distance between rebar and wall) and the distance between the rebars in flow direction. Both the concrete cover and the distance between rebars are determined by structural requirements [5]. As a result, only the concrete rheological properties can be varied to avoid the occurrence of dead zones. For each configuration, the rheological properties (plastic viscosity and yield stress) of the SCC flow were optimized to find the optimum plastic viscosity and yield stress to ensure dead zones are minimized and the formwork is filled adequately.

2. Governing Equation

The SCC flow is simulated as a single phase incompressible yield-stress fluid in a laminar flow regime. This fluid can be described by the continuity equation and the Cauchy momentum balance equation (ρ: fluid density, $\mathbf{u}$: fluid velocity vector, t: time, p: pressure, $\boldsymbol{\tau}$: stress tensor, and $\mathbf{g}$: gravity acceleration vector).

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{u}) \qquad (1)$$

$$\rho\frac{D\boldsymbol{u}}{Dt} = -\nabla p + \nabla\cdot\boldsymbol{\tau} + \rho\boldsymbol{g} \quad (2)$$

The constitutive equation for $\boldsymbol{\tau}$ in (2) is given in terms of plastic viscosity: μ_p, yield stress: τ_y, a correction parameter for avoiding singularity resulting from the yield stress implementation [6]: ε, deformation tensor, $\Delta = \nabla\mathbf{u} + (\nabla\mathbf{u})^T$, and shear rate, $\dot{\gamma} = \sqrt{\frac{1}{2}\Delta:\Delta}$.

$$\boldsymbol{\tau} = \left(\mu_p + \frac{\tau_y}{\dot{\gamma}+\varepsilon}\right)\Delta \quad (3)$$

Equation (3) is known as the Bingham fluid model which is used for modeling the behavior of yield-stress fluids, modified with ε to avoid the singularity when the shear stress is lower than or equals the yield stress. COMSOL Multiphysics® solves equations (1) to (3) using finite element methods.

3. Methods

3.1 Formwork parameters

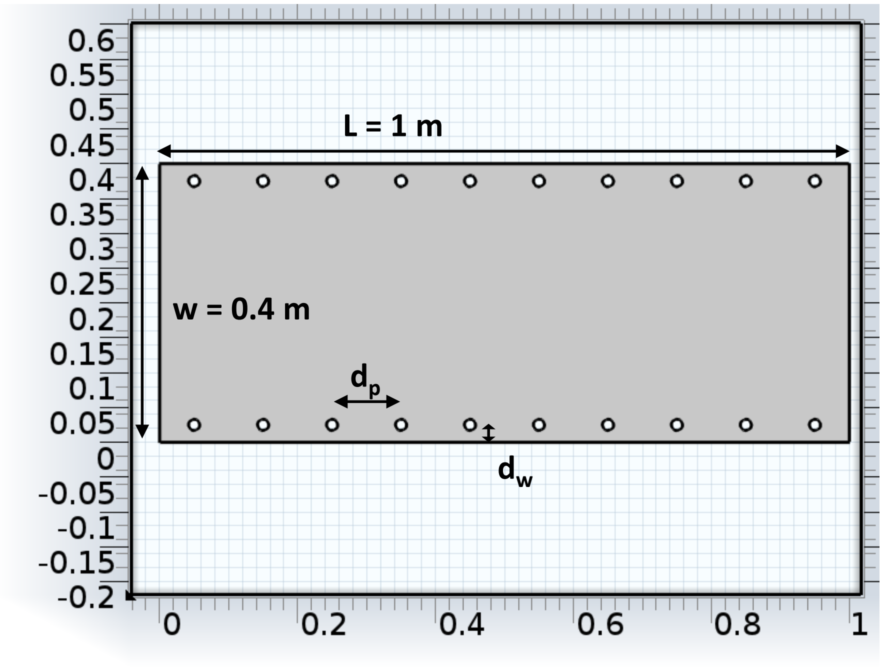


Figure 1. Formwork configuration (Case A-1)

As shown in Figure 1, the formwork is simulated as a rectangular channel with a length of 1 m and width of 0.4 m. The circular objects, with a diameter of 0.016 m, near each wall represent the rebars. The nearest distance between the center of a rebar and a wall, d_w, as well as the distance between the centers of rebars in flow direction, d_p, are varied for each case. Table 1 summarizes the rebar configuration and description of each case. Case A is for investigating the effect of d_w and Case B is for the effect of d_p.

A no-slip boundary condition is imposed on the channel walls and the rebar surfaces. The entrance effect was removed by adding an imaginary entrance and outlet with lengths of 0.3 m. Both the inlet and outlet average flow rates are set to $U_i=U_o=0.1$ m/s. The fluid density of the SCC is chosen as 2350 kg/m^3. The rheological properties (μ_p and τ_y) are chosen as described in section 3.2. A maximum fluid viscosity limit of 10^6 Pa.s (at very low shear rates) was maintained by adjusting ε for each case. A total of 10382 elements of triangular mesh were created. The 2D maps of the dimensionless velocity, $u^*=u/U_i$ and the dimensionless stress, $\tau^* = (\mu\dot{\gamma})/\tau_y$, are plotted to be used for identifying the dead zone (the unyielded zone with low velocity: both u^* and τ^* are less than 1).

Cases	d_w (m)	d_p (m)	Description
Case A-1	0.025	0.1	Small d_w
Case A-2	0.05	0.1	Large d_w
Case B-1	0.0375	0.05	Small d_p
Case B-2	0.0375	0.25	Large d_p

Table 1. Rebar configuration and description of each case

3.2 Rheological properties

In this study, the optimized rheological properties (a set of $\mu_p - \tau_y$) were searched along the line in the middle of the SCC zone in the rheograph, the $\mu_p - \tau_y$ map identified by Wallevik [7]. For each case, a simulation started with the highest μ_p (= 80 Pa.s) and the lowest τ_y (= 1 Pa). The pressure drop between the inlet and the outlet of the channel is also computed. Simulations with other rheological properties are performed, in the order indicated in Table 2. The specific combination of τ_y and μ_p which gives the highest possible yield stress and the lowest possible plastic viscosity without having dead zones was considered as the optimum. The pressure drop at the optimized set of the properties is also obtained to be compared with the with the pressure drop resulted from the set of the highest μ_p and the lowest τ_y.

Plastic Viscosity (Pa.s)	Yield Stress (Pa)
80	1
76	2.01
72	3.01
68	4.38
64	5.84
60	7.35
56	9.81
52	12.17
48	14.75
44	17.27
40	19.94

Table 2. The order of rheological properties (along the line in the middle of the SCC zone in the rheograph) for the optimization

4. Results and Discussion

4.1. Optimized Properties

The optimized rheological properties from each case are summarized in Table 3. The difference between the pressure drop at the highest plastic viscosity case and the pressure drop at each optimized case is also summarized in the same table.

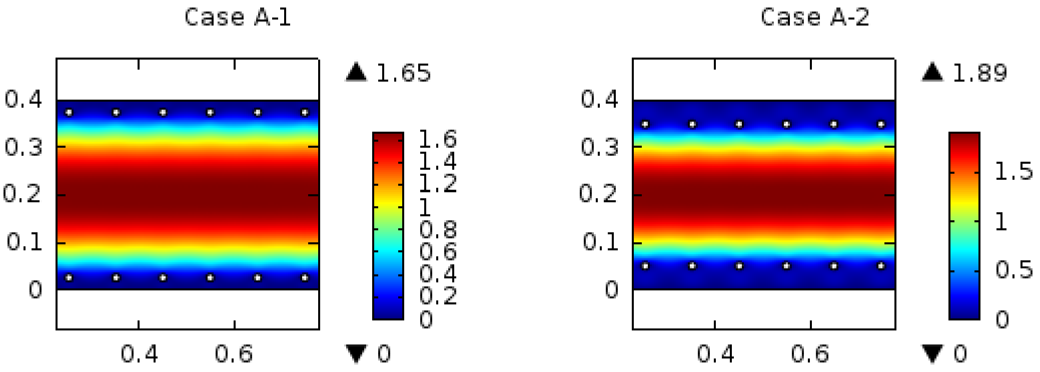
	Optimum Values	$\Delta P^{\mu=80}$-ΔP^{opt} (Pa)
Case A-1	$\mu_p = 56 \quad \tau_y = 9.81$	224.96
Case A-2	$\mu_p = 52 \quad \tau_y = 12.17$	363.64
Case B-1	$\mu_p = 72 \quad \tau_y = 3.01$	140.96
Case B-2	$\mu_p = 52 \quad \tau_y = 12.17$	246.67

Table 3. Summary of the optimum rheological properties and the pressure drop reduction.

The results in Table 3 indicate that mainly the presence of a lot of rebars (case B-1) has a significant influence on the occurrence of dead zones, as the optimum yield stress value is relatively low. With a relatively large rebar interspacing (d_p), the concrete cover (d_w) has only a minor influence on the optimized rheological properties. Increasing d_p and, to a minor extent, d_w allows for SCC with larger yield stresses, and thus lower plastic viscosities to be used inside the formwork, preventing the formation of dead zones.

4.2. Flow Pattern

Figure 2 shows the simulated flow patterns that resulted from the optimized properties in each case. In either case, the flow velocity at the center is higher than the average velocity (high velocity region) and the flow between the channel wall and the rebars are lower than the average velocity (low flow region). A more detailed analysis of the flow patterns is given in the next section.



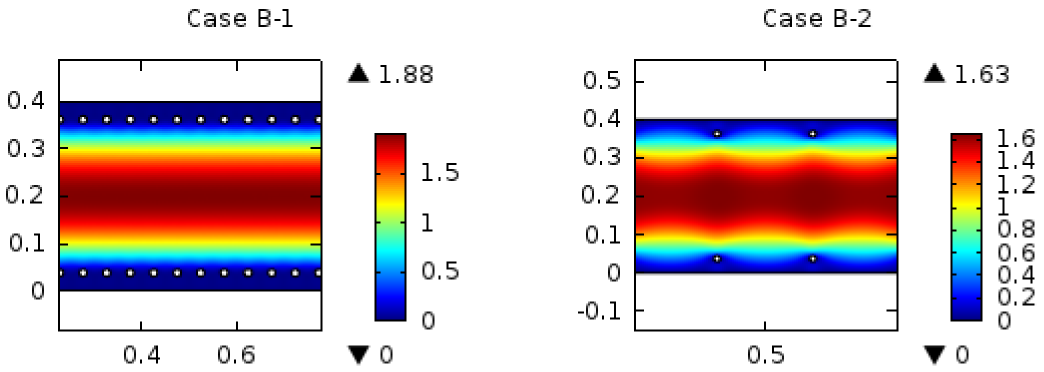


Figure 2. Simulated flow patterns (u*) from the optimized properties.

4.3. Shear Stress Distribution

Figure 3 shows the 2D map of simulated shear stress distribution from the optimized rheological properties at each case. Note here that the properties beyond the optimized values resulted in the dead zones (unyielded zone with low flow velocity) near channel walls (data not shown). Note that the unyielded zone at the center is not dead zone because its velocity is high (u*>1). As can be seen in Figure 3, the maximum shear stresses are concentrated around the rebars.

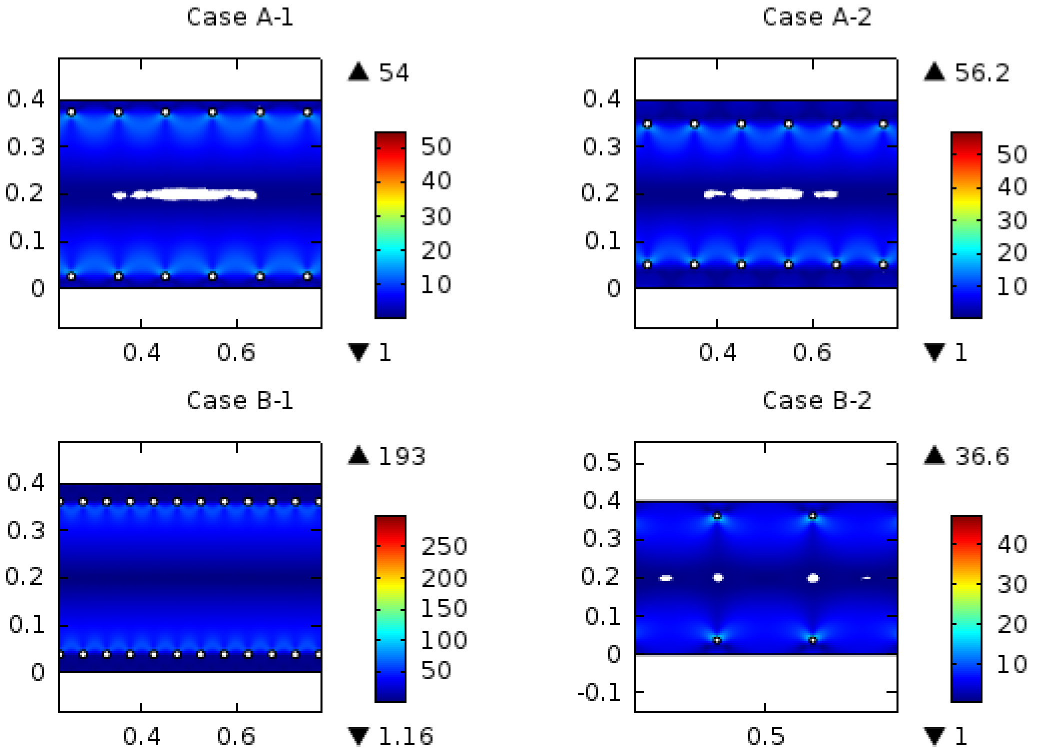
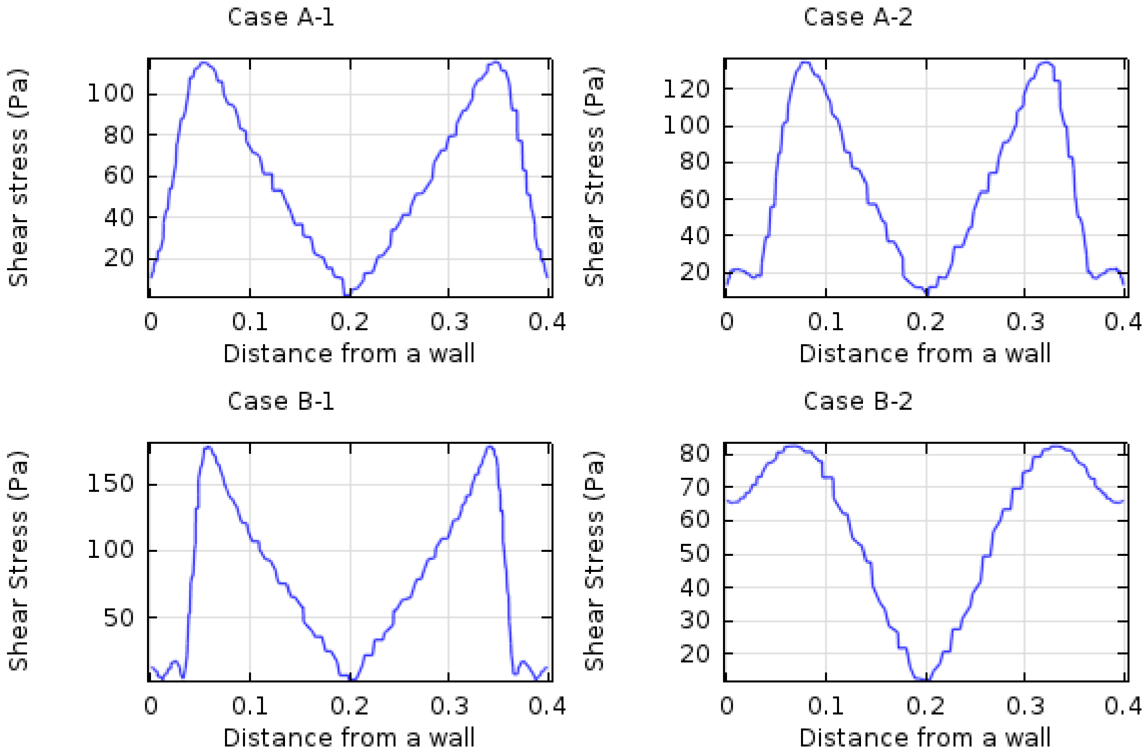


Figure 3. Simulated shear stress (τ*) from the optimized properties.

Figure 4 shows the shear stress profile in the cross sectional direction at a center position between rebars in the flow direction for the optimized rheological properties for each case. The highest stress values were located where the rebars are. As d_p increases (Case B-2), the stress value near a wall increases, which becomes similar to the stress profile for channel flow without rebars. On the other hand, with decreasing d_p and thus with increasing concentration of rebars, the shear stress between the rebars and the wall is close to zero, stopping the concrete flow in the concrete cover. When the rebars are close to each other, they act as a virtual wall and the concrete needs to be close to self-levelling to avoid the occurrence of dead zones.

As a practical consequence for Case B-1, the SCC in the cover is at rest during casting, except when self-levelling concrete is used. Dependent on the thixotropic build-up, the self-consolidation may be compromised leading to an increasing quantity of entrapped air. Furthermore, as the rebars create a virtual wall, a cold joint may occur between the concrete at rest in the cover and the concrete moving in the center of the wall, which may reduce the bond behavior between the two concrete layers and between the concrete and the rebars.


Case A-1

Case A-2

Case B-1

Case B-2

Figure 4. Simulated shear stress (τ^*) profile as a function of the distance from a wall (y-direction) at x=0.5m (x-direction: flow direction).

5. Conclusions

This study investigated the optimization of the rheological properties of SCC for formwork filling in presence of rebars. COMSOL Multiphysics® was used to simulate the flow pattern and the shear stress distribution inside the formwork for each configuration of rebars and each set of rheological properties. The rheological properties were optimized to find the the maximum τ_y and minimum μ_p which still avoided the occurrence of dead zones. The results (Table 3) suggest that with increasing d_p or, to a lesser extent, d_w, the combination of lower μ_p and higher τ_p can be used to obtain adequate SCC flow in the formwork, Furthermore, this results in a reduction of the energy needed for the placement of concrete.

The numerical simulations show also that for a dense reinforcement grid (similar to case B-1), the SCC needs to have self-levelling properties to avoid the dead zones in the concrete cover. For small distances between the rebars, the concrete flows between two “virtual walls” created by the rebars. This means that after the space between the formwork and the rebars is filled, the concrete flow stops if the yield stress of the concrete is not sufficiently low. This can lead to entrapment of air in the concrete cover or the creation of a cold joint in the concrete at the rebar location, which could lead to premature deterioration of the concrete cover of our infrastructure.

This project has also shown that numerical simulations can be a quick and easy tool to initially assess optimum concrete properties for specific applications. Performing numerical simulations can save a substantial amount of money, materials and labor to explore specific problems. By means of a short series of experiments, the conclusions of the numerical simulations can be verified and easily implemented in practice.

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7. Acknowledgements

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