# MODEL OF SCC FLOW THROUGH REINFORCED SECTIONS: EXPERIMENTAL VALIDATION

Ksenija Vasilic[1*], Wolfram Schmidt[1], Hans-Carsten Kühne[1] and Nicolas Roussel[2]

[1] BAM, Federal Institute for material research and testing, Berlin GERMANY.
[2] IFSTTAR, Université Paris Est, FRANCE.

* corresponding author: ksenija.vasilic@bam.de

## ABSTRACT

*This study focuses on concrete flow in presence of obstacles and develops a mathematical model and a computational approach for SCC flow through reinforced formworks. In order to decrease high computational times needed to simulate castings through reinforced elements, an innovative approach to model the reinforced sections as porous media is proposed here. In the previous work, this numerical model is proved able to simulate the free-surface flow of non-Newtonian fluids through the reinforcement networks. In the present study, the applicability of the model on the concrete flow will finally be proved. The large-scale form-filling experiments with SCC will be conducted and the experiments will be simulated using the proposed numerical model. The numerical model will then be validated through the comparison of the experimental results and the results of the numerical simulations.*

**Keywords:  rheology; numerical modelling; reinforcement; porous medium**

## INTRODUCTION

In the recent years, the numerical simulations of fresh concrete flow are becoming a powerful tool for prediction and optimisation of concrete castings [1, 2]. They can help engineers to avoid unwanted expensive mistakes on site, especially in case of complex and highly reinforced elements. However, the numerical simulations of castings through reinforced elements are extremely time consuming, since one has to model rebars one by one. In order to decrease the computational time, we proposed to model the flow of SCC through a reinforcement zone as a flow of a non-Newtonian fluid through a porous medium (PM) [3, 4, 5]. The model couples a fluid dynamics approach for concrete flow and a macroscopic model that includes the influence of the porous medium (formed by rebars) on the flow. In the previous studies, the model was implemented into the computational fluid dynamics (CFD) software FLUENT and a preliminary experimental validation on the small scale experiments with Carbopol gel was conducted. It was proved that the implemented model leads to a significant decrease in total computational time and that it is able to successfully simulate the flow of non-Newtonian fluids through reinforcement networks [3]. The next major simplification of this approach is that one assumes that the concrete is a continuum, approximating its complex structure with a one-phase model and describing its behaviour with the Bingham model. The large-scale experiments with SCC are the final step to prove that, under certain limitations, this rough approximation is valid. Through comparison of the experimental results and the results of the corresponding numerical simulations, the aim of this contribution to prove the applicability of the proposed model on the flow of cementitious materials in the presence of reinforcement .

In order to choose a suitable experimental setup, a series of numerical studies with different geometries of the filling form and reinforcement dispositions were performed, tuning them until the optimal ones were selected. The form filling experiment was built up and the experiments with two different SCC mixes were performed. Subsequent to the experiments, the numerical simulations using the approximate porous medium geometry and model were conducted. Finally, the experimental results and numerical simulations were compared and discussed.

### Porous medium analogy

From the modelling point of view, fresh concrete can be considered as a fluid when the granular nature of the material can be neglected compared to the hydrodynamic interactions within the material [6, 7].  This assumption is fulfilled for stable materials with lower contents of coarse aggregates such as concretes with slumps higher than 15cm and Self Compacting Concrete (SCC) [8], so they therefore can be described as

homogeneous non-Newtonian fluids. In the following is furthermore assumed that the blocking does not occur and the model developed here is limited to stable, non-segregating and non-blocking concretes. The most common constitutive equation used for concrete flow is derived from the Bingham model and can be written as:

$$\eta_{app} = \left( \frac{\tau_0}{\sqrt{2D_{II}}} + \eta_{pl} \right) \tag{1}$$

where $\eta_{app}$ is the apparent viscosity, $D_{II}$ is the second invariant of the strain rate tensor (it reduces to the shear rate $\dot{\gamma}$ in 2D simple shear flow problems), $\tau_0$ and $\eta_{pl}$ are the yield stress and the plastic viscosity of the material respectively. The fluid is assumed to be incompressible and the mass and momentum conservation equations are given as follows:

$$\underline{\nabla} \cdot \underline{v} = 0, \quad \rho \frac{D\underline{v}}{Dt} = -\underline{\nabla} p + \underline{\nabla} \cdot \underline{\underline{S}} + \rho \underline{g} \tag{2}$$

where $\underline{v}$ is the local velocity vector, $\rho$ is density, $p$ is pressure and $\underline{g}$ denotes gravity. The influence of the rebars (i.e. of the porous zone formed by rebars) on the flow is modelled by the addition of a momentum source term S to the standard momentum flow equations (the right side of the momentum equation in (2)):

$$S_i = -\frac{\eta_{app}}{k_i} v_i \tag{3}$$

where $S_i$, $k_i$ and $v_i$ are source term, permeability and viscosity in the direction $i$ respectively. For non-Newtonian materials, the local apparent viscosity $\eta_{app}$ depends on the local strain rate within the material. The local strain rate within the network is unknown and is a complex function of the geometry and configuration of the steel bars. Therefore a so-called "apparent" shear rate within the medium is defined here:

$$\dot{\gamma}_{app} = \frac{\alpha \cdot v_i}{\sqrt{k_i \cdot \phi}} \tag{4}$$

where $\phi$ is porosity and $\alpha$ is a shift factor [9, 10]. By introducing the apparent shear rate $\dot{\gamma}_{app}$ into (1) and then the obtained local apparent viscosity $\eta_{app}$ into (3), the expression for the source term becomes :

$$S_i = -\frac{1}{k_i} \left( \frac{\tau_0 \cdot \sqrt{k_i \cdot \phi}}{\alpha} + \eta_{pl} v_i \right) \tag{5}$$

In this final equation there are three unknown parameters: $\phi$, $k$ and $\alpha$. The porosity $\phi$ can easily be calculated from the geometry; the permeability $k$ is a measure of

topology of the medium and it is calculated from the numerical simulations with a Newtonian fluid. The third unknown parameter depends both on the topology and on the material flowing through the network. In [3] a methodology to compute the values of $\alpha$ for a large range of Bingham numbers, characteristic for flows of cementitious materials, was proposed.

This model is implemented into the commercial CFD software FLUENT. Within the "porous zones" the standard equations for Bingham materials are changed so that they include the influence of the porous medium on the flow. This is done by implementing so called User Defined Functions (UDF) for the extra source term  Si (additional pressure drop) within the porous medium zone according to equation (5). For the purpose of this study, the model is slightly simplified and the source term Si is added only in one dominant flow direction.

## EXPERIMENTAL SETUP

Prior to the experiments, a series of numerical simulations were performed in order to find the optimal experimental setup, experimental procedure and concrete mix. There were several specific prerequisites that were guidelines here. We searched namely for a form-filling experiment: concrete should be poured in a geometrically simple form that contains reinforcement bars. The experiment is to be designed as realistic as possible and as long as dimension limits allow, one should use realistic mixture and reinforcement bars. Concrete should flow through several different reinforcement zones, influencing the concrete behaviour in dissimilar ways. To be able to observe the flow front during the experiment, the front walls should be constructed from a transparent material such as Plexiglas. In most of the practical applications the flow of concrete is laminar and should be accordingly kept laminar within the experiment.Since the dispersed phase is not included into the simulation, the used concrete should not segregate. The proposed model is limited to non-blocking concretes, so in order to prevent blocking the minimum distance between the bars should not be less than $d_{max}$ + 5 mm and less than $2d_{max}$ ($d_{max}$ being maximum particle diameter).

After several numerical tests, where geometries, bars position, pouring velocity and boundary conditions were varied, the final geometry was chosen and built up (Cf. Fig. 1). It consists of a rectangular container dimensions 2980 x 500 x 700 mm, where the concrete is poured in. In order to avoid turbulences, a ramp is constructed on one side of the box, so that concrete can slowly flow into the form. There are four different reinforcement zones within the box; the diameter of all the rebars is 10 mm, while the distance between the bars is 50, 20, 20 and 40 mm in the zones 1, 2, 3 and 4 respectively. Taking into account all the limitations concerning blocking, the maximum particle diameter $d_{max}$ = 8 mm was decided on.

*Figure 1. The chosen experimental geometry with four reinforced zones: top view (below), front view (above)*
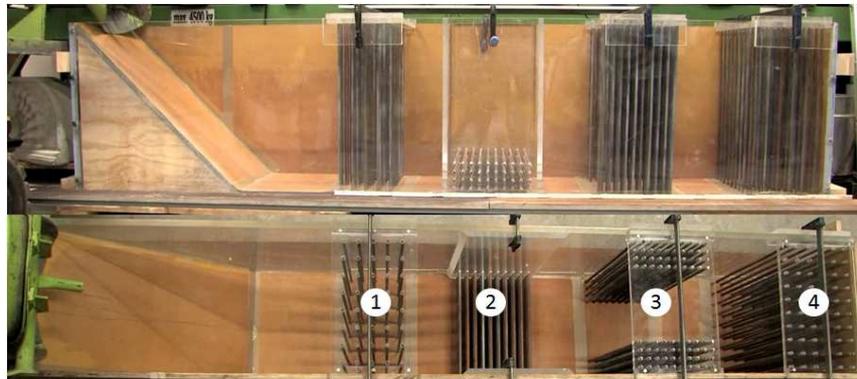
## EXPERIMENTAL STUDIES AND NUMERICAL SIMULATIONS

The experimental procedure involves several (overlapping) phases: mixing of concrete, parameter determination (before, during and after experiment yield stress and viscosity of the used concrete are determined), slow pouring of concrete into the form and measurements of the final concrete shape. Firstly, 400 l of concrete was mixed over a period of 10 minutes. 350 l was poured into a mobile hopper, then poured from the hopper into a funnel (Cf. Fig. 2, left) and used for the flow experiment. The remaining 50 l was used for the investigation of the material properties: two minutes before the funnel gate was opened, the slump flow, LCPC-box flow distance and the V-funnel efflux time were measured and the G-yield and H-viscosity were determined using the Rheometer-4SCC. Directly after these measurements, the funnel gate was opened and the concrete was allowed to freely flow into the Plexiglas container. Hereby, the flow front development was videotaped from the side and from above. When the flow stops, the final shape of the flow front was measured.

*Table 1: Mixture composition for the SCC mixtures used in the experiments*

|  |  | SCC1 | SCC2 |
|---|---|---|---|
| Constituent | Specific Gravity [-] | Net weight per 1000l [kg/m³] | Net weight per 1000 l [kg/m³] |
| Cement | 3.12 | 296 | |
| Limestone filler | 2.74 | 296 | |
| Water | 1.0 | 180 | |
| Sand (0 - 2.0) | 2.60 | 662 | |
| Aggregate (2.0 - 8.0) | 2.60 | 891 | |
|  |  | admixture adjustment | |
| Superplasticizer | 1.07 | 2.15% bwoc | |
| Stabilising agent |  | 0.017% bwo water | - |

*Figure 2. Experimental setup, Plexiglas container with four reinforcement zones and the pouring funnel (left). Numerical simulation, reinforcement zones modelled as porous media (right).*

In this paper the results of the experiments with two different concrete mixes are shown (Cf. Tab. 1). In order to make sure that no influences of different volumetric ratios of paste to aggregates occur, the same mixture composition was chosen for both concretes. Since within certain thresholds, the addition of polycarboxylic superplasticizers (PCE) predominantly affects the yield stress without having crucial effects on the viscosity, the superplasticizer addition can be used as a controlling parameter for the yield stress adjustment. However, the amount of effective PCE also strongly affects the workability retention, and for the good conduction of the experiment a long workability time had to be adjusted. Thus high PCE dosages are required in order to provide sufficient open time and therefore a mixed approach is preferred, in which the rheological properties are adjusted by PCE and stabilising agent. The two SCC types differ only by their content of stabilising agent. Due to its strong effect on yield stress, stabilising agent based on potato starch was used.

The yield stress values for SCC1 and SCC2 were derived from correlation curves between G-Yield values determined by the Rheometer-4SCC and the values obtained from slump flow and LCPC box measurements according to [11]. The values for viscosity were estimated by the correlation factors between the Rheometer-4SCC and the ConTec Viscometer 5 provided by the producer. As the Rheometer-4SCC cannot precisely determine viscosity values, based on the experimental measurements and preliminary numerical simulations, the viscosity was estimated to be around several tens of Pas. Since we are in this study interested only in the final shape of the material, which in flows where inertia can be neglected depends only on yield stress, the approximate value of viscosity can be considered sufficient. Thus the material parameter values used for numerical simulations were: $\tau_0$ = 71 Pa and $\eta_{pl}$ = 20 Pas for SCC1 and $\tau_0$ = 36 Pa and $\eta_{pl}$ = 20 Pas for SCC2. The numerical simulations of the experiment are conducted using software FLUENT where the reinforced zones are modelled as porous media (Cf. Fig. 2, right).

# RESULTS AND DISCUSSION

The developed numerical model was validated through the comparison of the experimental results and the results of the corresponding numerical simulations (cf. Fig. 3 and Fig. 4). The diagram in Fig. 3 shows the comparison of the experimentally and numerically obtained flow front when material stops flowing for the SCC1 and SCC2. Fig. 4 gives a visual representation of both experimental and numerical results obtained. The results show a fairly good congruence between the numerically and experimentally obtained data. The discrepancies in shape of the obtained curves, are most likely the consequence of the 1D simplification used in this study, namely the addition of the source term only in one dominant flow direction. The results also showed, that the model is able to predict the behaviour of different concretes, having different rheological properties.

*Figure 3. The material shape when the flow stops, experiment versus numerical simulation. High yield stress concrete $\tau_0$ = 70 Pa (SCC1) and medium yield stress concrete $\tau_0$ = 36 Pa (SCC2).*
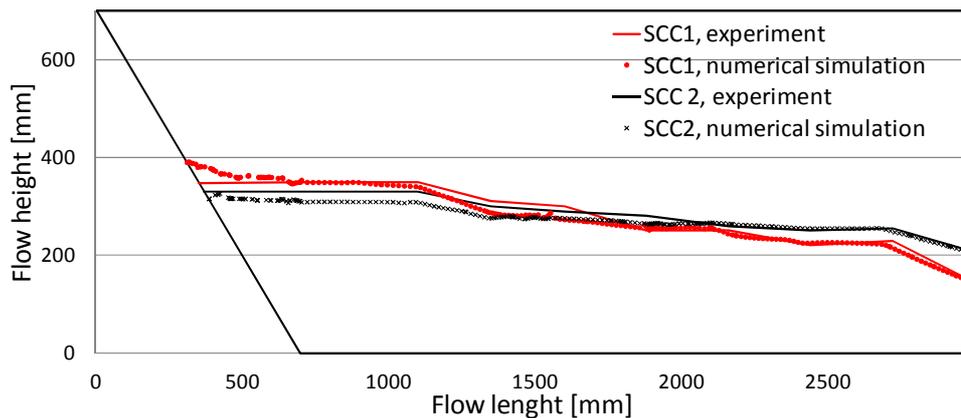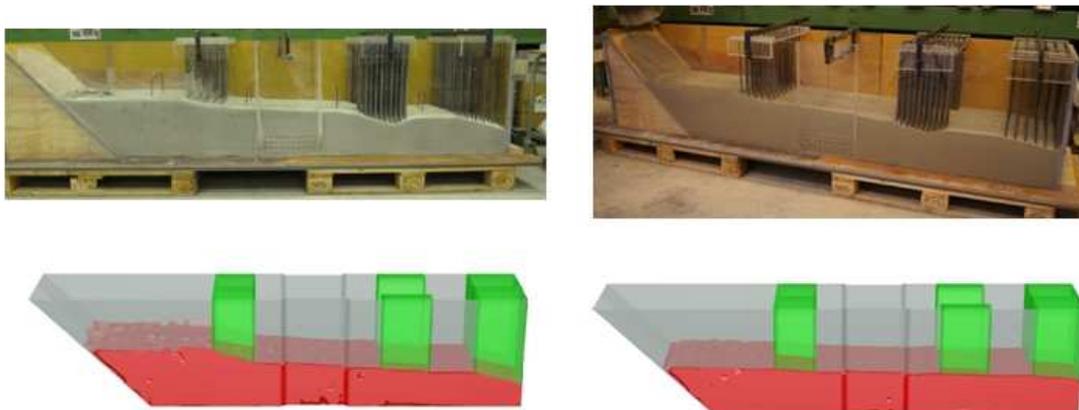


*Figure 4. The material shape when the flow stops, experiment versus numerical simulation, visual illustration. SCC1 with $\tau_0$ = 70 Pa (left) and SCC2 with $\tau_0$ = 36 Pa (right)*

# SUMMARY

This paper presented an experimental validation of the mathematical model for flow of concrete through reinforced sections, modelled as a porous medium. The good match between the simulated and experimental results, proved that the proposed model is able to simulate the free-surface flow of concrete through reinforcement networks. The discrepancies between the numerical and experimental results, imply that the further development of the 3D formulation of the model equations is necessary. The future work will focus on the definition of all the model parameters and equations in 3D (permeability, source term etc.) and the implementation of the modified 3D model into the CFD code.

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