Simulation of the Test Method "L-Box" for Self-Compacting Concrete

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ABSTRACT

Both filling and passing ability are important properties to be considered for self-compacting concrete. This paper presents simulations of the L-box test and corresponding experiments. The assumption of a continuum mechanical approach, where the fluid rheology is described by the Bingham model, is tested.

INTRODUCTION

Self-compacting concrete (SCC) has been applied for approximately 15 years. The concept of a concrete that does not need vibration to become compacted has potential advantages compared to conventional types of concrete, e.g. with regard to productivity, quality, architectural design, and working environment. Furthermore, in places where vibration is impossible due to form geometry and reinforcement configuration, the high fluidity of SCC may enable concrete to flow over longer distances and into every corner of the form (Skarendahl[1]).

SCC has been applied in both the ready mix and pre-cast industry. In Denmark the annual amount of SCC produced has reached approximately 20 % and 30 % in the ready mix and pre-cast industry, respectively. On an international level it seems that the use of SCC has temporarily stagnated [Newsletter[2]]. One reason for the stagnation appears to be the segregation resistance of SCC, which is lower than that of conventional concrete. It should be noted that the definition of SCC varies.

Other important properties are the filling and the passing ability. To avoid misunderstandings this paper will distinguish between the terms passing ability and blocking. *Passing ability* will refer to the ability of the concrete to pass reinforcement bars while remaining homogenous, whereas *blocking* will refer to aggregate accumulation behind reinforcements (instability). Instability either in form of segregation or blocking may eventually cause variations in the structural properties.

For further development and use of SCC, simulations of the form filling behaviour including passing ability, blocking resistance and segregation resistance may provide a means for optimising form filling.

Simulations of the flow of suspensions in restricted areas or around barriers have been undertaken by means of the distinct element method (Noor et al.[3] and Petersson et al.[4]) and dissipative particle dynamics (Martys et al.[5]). By means of the distinct element method, simulations were carried out on SCC flow during testing, e.g. in the so-called L-box (Noor et al.[3]).

L-box

The L-box is one test method developed to assess the passing ability and blocking resistance of SCC (Billberg[6]). Fig. 1 shows the geometry of the L-box applied for the investigations presented in this paper. A moveable gate divides the vertical and the horizontal section. The vertical section is filled with concrete and the gate is lifted to allow concrete to flow past the reinforcement bars and into the horizontal section. The diameter and spacing of the reinforcement bars may be varied according to the reinforcement configuration in the actual structure.

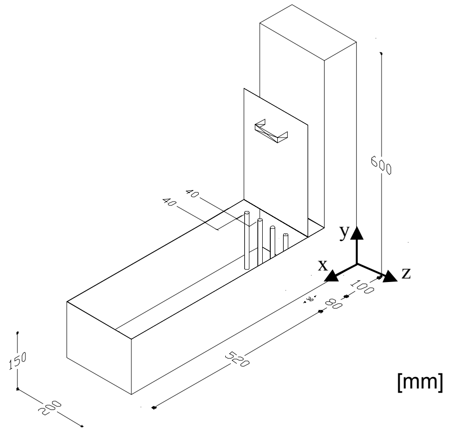


Figure 1. The L-box applied in these investigations. Shown with four bars ($D_{bar} = 10$ mm).

To assess the passing ability, the ratio between the concrete height at the end of the horizontal section, and the height of the remaining concrete in the vertical section has been proposed (H2/H1). This is usually referred to as the blocking ratio and a minimum value of 0.8 has been suggested (Billberg[6]). However, to avoid erroneous conclusions, it seems that the blocking ratio should only be considered when segregation and/or accumulation of aggregate behind the reinforcement does not occur. The time to reach 20 cm and 40 cm from the gate (T20 and T40) corresponding to x = 350 mm and x = 550 mm has been proposed as an indication of the filling ability but no values have been generally agreed on (Efnarc[7]).

Objective

The objective of the investigations presented in this paper is to verify a continuum mechanical approach for simulation of SCC flow in narrowing gaps (not blocking) by means of a FEM formulation of the Navier-Stokes equations for incompressible fluid flow.

As an example, the L-box is considered.

The investigation is part of a project on the simulation of the form filling ability of SCC in full-scale forms (Nordic Concrete Research[8]).

The experiments include testing of mortar and concrete.

SIMULATION

Simulation of the L-box is based on a Galerkin FEM formulation of the Navier-Stokes equation. The material properties in a continuum approach are directly related to a physical viscosity function. However, it does not provide an immediate assessment of the blocking resistance due to the absence of particles in a continuum approach.

Navier-Stokes Equations for Incompressible Fluid Flow

For a single-phase, viscous fluid the law of conservation of mass, momentum and energy describes the fluid flow. In this investigation, isothermal conditions are assumed for which reason the conservation of energy is not considered. Conservation of mass under the assumption that density, ρ, is constant results in the equation

$$(\nabla \cdot \mathbf{v}) = 0 \qquad (1)$$

where **v** is the velocity vector (Bird et al.[9]).

Conservation of momentum results in the equation

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g} \qquad (2)$$

where **t** is time, **g** is the body force per unit mass, and $\boldsymbol{\sigma}$ the stress tensor given by

$$\boldsymbol{\sigma} = p\boldsymbol{\delta} + \boldsymbol{\tau} \qquad (3)$$

where p is pressure, δ is the unit tensor, and τ is the deviatoric stress tensor associated with the viscosity of the fluid.

The rheological properties of the fluid constitute the physical relation between the deviatoric stress tensor and the strain rate tensor.

$$\boldsymbol{\tau} = 2\eta \dot{\boldsymbol{\gamma}} \qquad (4)$$

$$\dot{\boldsymbol{\gamma}} = \frac{1}{2}\left(\nabla \mathbf{v} + (\nabla \mathbf{v})^{T}\right) \qquad (5)$$

where η is the viscosity and $\dot{\gamma}$ is the strain rate tensor. If the viscosity function η is not constant it is referred to as a non-Newtonian viscosity and (2) may be written as

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \nabla \cdot (2\eta \dot{\boldsymbol{\gamma}}) + \rho \mathbf{g} \qquad (6)$$

where D/Dt is the material derivative.

COMPUTATIONAL MODEL

As earlier mentioned, a Galerkin FEM approach is applied to solve the equations (Fidap[10]). In the momentum equation both the convective term and a non-Newtonian viscosity function will contribute to non-linear algebraic equations for the field variables, which are solved by applying an appropriate iterative scheme.

In general, concrete flow includes a moving boundary in terms of a free surface of arbitrary shape. To be able to simulate the free surface deformations, the surface is characterized by a volume-of-fluid representation on the computational non-moving mesh, and a volume tracking method determines advection of the fluid. The fluid volume is represented by means of a marker concentration F. The advection of the marker concentration is governed by

$$\frac{\partial \mathbf{F}}{\partial \mathbf{t}} + \mathbf{v} \cdot \nabla \mathbf{F} = \mathbf{0} \qquad (7)$$

where F is equal to unity within the tracked volume and zero outside. Every element in the mesh has a fractional fill state between zero and unity (Fidap[10]). The volume tracking method consists of two steps. The fluid volume is reconstructed on the basis of the fractional fill state and represents an estimate of the spatial location of the fluid within the mesh. Then, the FEM equations are used to calculate the kinematics based on the fluid boundary, and from the velocity field the fluid is advected leading to new fractional fill states (Fidap[10]).

Because of the way the shape of the free surface is captured, it has been decided to use bi-and trilinear interpolation for velocity rather than, for instance, fewer elements with a bi-and triquadratic interpolation.

Therefore the flow domain models consist of 8-node brick elements and 4-node quadrilateral elements in 3-d and 2-d, respectively. The mesh density has been optimized under considerations of convergence, accuracy, free surface capture, and calculation times.

The pressure is approximated according to a discontinuous mixed formulation where pressure is included in the equations solved for unlike in a penalty approach (Gresho et al.[11]).

At all interfaces between the concrete and the sides of the L-box, the velocity is constrained to zero under the assumption that slip does not occur.

In the 3-d model symmetry across the xy-plane at z=-100 mm is assumed and only half of the L-box is modelled.

EXPERIMENTAL

The L-box experiments presented in this paper include one mortar and concrete test. The concrete was tested as part of an experimental program on form filling with SCC at one of the ready mix plants of 4K-Beton A/S. The mortar has been tested in the laboratory at the Technical University of Denmark, Department of Civil Engineering.

Materials

The maximum size aggregate size of the concrete and mortar is 20 mm and 4 mm, respectively. Both the mortar and the concrete contains cement, fly ash, and silica fume as well as a superplasticizer.

Rheological Properties

The rheological properties have been measured in a concentric viscometer (BML viscometer). Previous studies on the rheological properties of SCC have indicated a non-Newtonian behaviour including a yield stress value (e.g. Nielsson et al.[12] and Farraris et al.[13]). In general, the rheological properties of concrete are time-dependent (thixotropic) for which reason the flow resistance should be interpreted at steady-state (Geiker et al[14]). Fig. 2 shows rheological measurements, and Fig. 3 shows interpreted torque values versus rotational velocity. The measuring procedure applied includes 8 different rotation velocities with a maximum and minimum value of 0.57 s^{-1} and 0.05 s^{-1}, respectively. To obtain steady state flow and limit segregation testing have been undertaken for 15 s and 10 s at each rotational velocity for the mortar and concrete test, respectively.

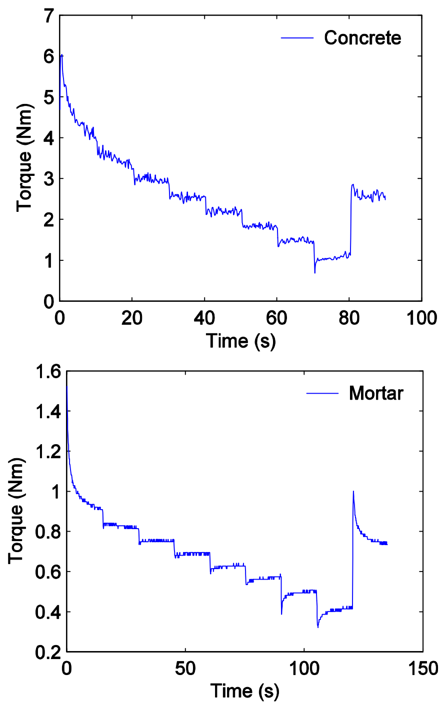


Figure 2. Rheological measurements on concrete and mortar.

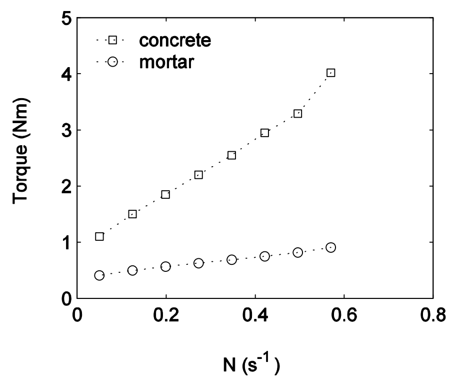


Figure 3. Torque vs. rotational velocity.

Leaving out the points where equilibrium is not reached, and where plug flow occurs, the results of the tested mortar and concrete indicate a linear behaviour according to the ideal Bingham viscosity given by

$$\eta\left(\dot{\gamma}\right) = \eta_{pl} + \frac{\tau_0}{\dot{\gamma}} \qquad (8)$$

where η_{pl} is the plastic viscosity (Pa·s), τ_0 is the yield stress (Pa), and $\dot{\gamma}$ is the magnitude of the strain rate tensor.

The results show some thixotropic behaviour. It is, however, not considered in the present simulations. The modelling of thixotropic behaviour has recently been undertaken by Wallevik[15] based on a modification of the Hattori-Izumi theory.

Table 1 shows the rheological properties according to the Bingham model and results from the slump flow test, the total spread, SF, and the time to reach a diameter of 50 cm, T50.

Table 1. Bingham parameters and slump flow values for mortar and concrete

	τ_0 [Pa]	η_{pl} [Pa·s]	SF [mm]	T50 [s]
Concrete	49	16	610	2.3
Mortar	39	5	670	0.95

Testing Procedure

The L-box geometry applied for the mortar corresponds to the one in Fig. 1 with a clear spacing between reinforcement bars of 30 mm. The L-box geometry applied for testing of the concrete was slightly different, and only 3 bars were included with a clear spacing of 25 mm. The test has been performed according to the description presented under “L-box” and at the same time as the rheological properties were measured.

RESULTS AND DISCUSSION

For simulation purposes it is initially investigated whether it is reasonable to model the L-box in 2-d (channel flow) in order to limit the requirements to computational capacity. In 2-d there is no effect from the boundaries in the xy-plane. For this purpose simulations of the L-box without reinforcement have been carried out for a particular choice of viscosity, in this case a Newtonian fluid having a viscosity of η = 20 Pa·s. Fig. 4 shows the spread into the horizontal section (x-direction) as a function of time.

The results indicate that the viscous contribution due to the shear introduced by the boundaries (xy-plane at z = 0 and z = –200 mm) influences the flow into the horizontal section of the L-box.

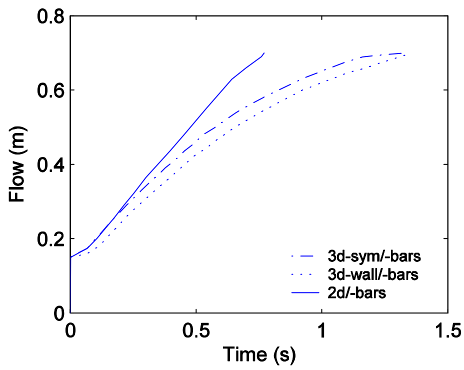


Figure 4. 2-d and 3-d simulation of flow into horisontal section of L-box (no reinforcement). η = 20 Pa·s. Sym = plane of symmetry. Wall = flow at the boundary, z = 0 and z = –200 mm. /-bars = no reinforcement. /+bars = reinforcement.

For instance, the time to reach the end wall (x = 700 mm) is 0.70 s and 1.20 s for “2d/-bars” and “3d-sym/-bars”, respectively.

Therefore, it seems that it is not reasonable to assume channel flow in the L-box, though, it is expected that this effect will decrease for lower viscosities. The H2/H1 value in both 2-d and 3-d will eventually be equal to 1 due to the properties of a Newtonian fluid.

Fig. 5 shows the flow of the mortar and concrete near the reinforcements bars. For the concrete, some blocking of aggregates occurs between the reinforcement.

Therefore, in order to verify the computational approach of a continuum, simulations are only compared with the mortar test.

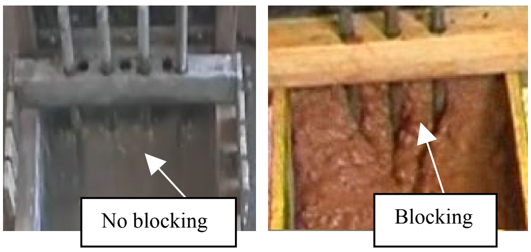


Figure 5. Flow of mortar (left) and concrete (right) near the reinforcement in the L-box.

Fig. 6 shows the results from the experiment and simulation of the mortar tested in the L-box, when reinforcement has been included. Fig. 7 shows the same 3-d simulation, however, without reinforcement. For comparison the 2-d simulation without reinforcement has been included in both illustrations (as in Fig. 4).

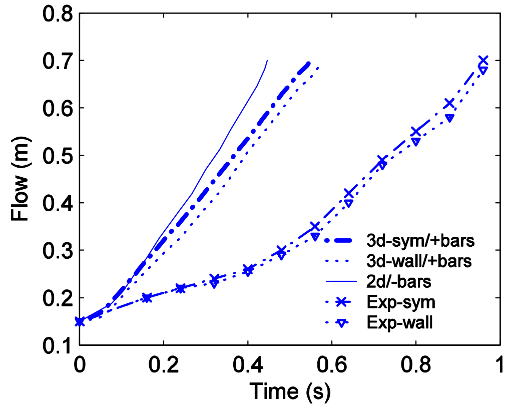


Figure 6. Simulation and experiments of Bingham fluid in the L-box. τ_0 = 39 Pa, η_{pl} = 5 Pa·s. Sym = plane of symmetry. Wall = flow at the boundary, z = 0 and z = –200 mm. /-bars = no reinforcement. /+bars = reinforcement. Exp = experiment.

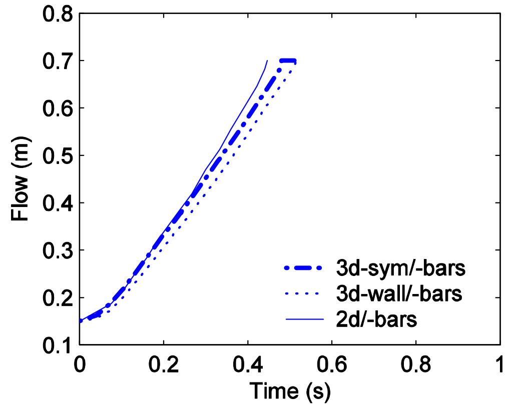


Figure 7. Simulation of the L-box for a Bingham fluid. τ_0=39 Pa, η_{pl}=5 Pa·s._Sym = plane of symmetry. Wall = flow at the boundary, z = 0 and z = –200 mm. /-bars = no reinforcement.

As expected, the simulation shows that the reinforcement bars retain the flow into the horizontal section e.g. compare “3d-sym/-bars” and “3d-sym/+bars”. Furthermore, though a yield stress is included, the spread in the plane of symmetry (no reinforcement) is more similar to that of the 2-d model due to a low plastic viscosity (Fig. 7 vs. Fig. 4).

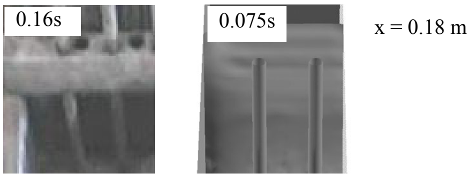
During the period of time (until approximately 0.56 s), the simulation does not seem to correspond to the experimental results. However, the main reason for the deviations observed seems to be caused by the time it takes to lift the gate in the experiment. For the simulation, it is assumed that the plate withholding the mortar is removed in an instant, which proves not to be the case in the experiment; Fig. 8 shows photos from the experiment and visualizations of the flow simulation at different spreads. Having reached 0.56 s, where the gate is fully lifted, the flow is at a sligthly lower rate. Moreover it is also possible that the rheological properties may deviate from those determined in the viscometric measurements.

Taken the above mentioned issues into consideration and comparing the flow visualizations with the corresponding photos from the experiments, a continuum approach seems applicable in domains including reinforcement, when blocking does not occur.

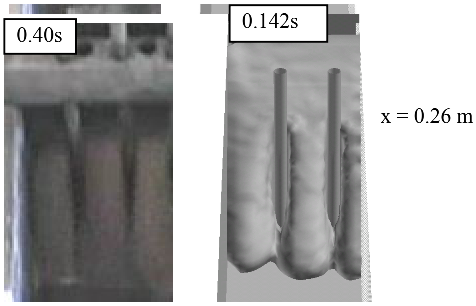
The slip effect has not been included in the simulations presented. Therefore, the surfaces of the L-box were dried to avoid as little experimental error as possible. Further investigations will look into the effect of lifting the gate and the slip effect.

To include blocking of aggregates, ongoing investigations are carried out to develop a micro-mechanical model on the blocking resistance of suspensions, which may be combined with the continuum flow.

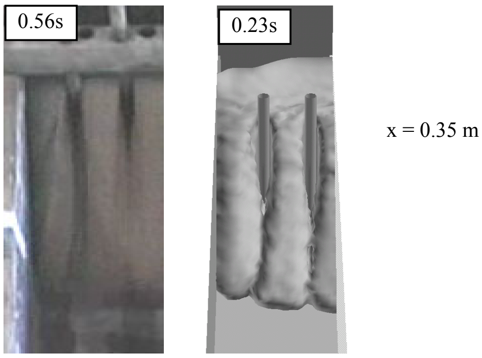
The H2/H1 equals 1 in both the experiment and the simulation. Actually, the simulation shows an overflow when the end wall is reached (x = 700 mm). The same overflow is not observed in the experiment where a maximum height of approximately 11 cm is reached, which is 2 cm above the final level (where H2/H1=1).



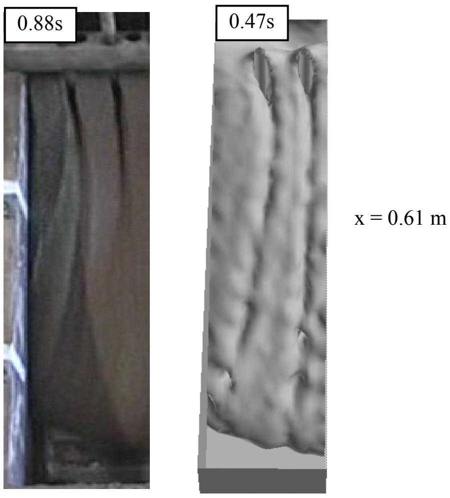
The gate is lifted 1 cm above bottom



The gate is lifted 75mm above bottom (half)



The gate lifted 150mm above bottom (full)



Flow of 0.61m into the horizontal section

Figure 8. Photos from experiments (left) and visualization of simulations (right) at the same spreads but different times.

CONCLUSION

A continuum mechanical approach has been presented for simulation of concrete flow in narrowing gaps as part of an overall aim of simulating form filling with SCC. As an example the L-box was studied.

The simulations have been compared with experiments. When taking the effect of lifting the gate in the experiment into consideration, the results indicate that in conditions where blocking does not occur, it is possible to simulate the flow in the L-box by a continuum mechanical approach where the fluid rheology is described by the Bingham model.

In general, comparison of 2-d and 3-d simulations showed that it is not reasonable to simulate the plane of symmetry in a 3-d model by that of a 2-d model due to the viscous effect.

Further investigations will be carried out to assess the effect of lifting the gate as well as the slip effect.

It is expected to include blocking by combining the continuum flow with that of a micro-mechanical model on the blocking resistance of suspensions.

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