COMPUTER-AIDED MODELLING AND SIMULATION OF SELF-COMPACTING CONCRETE FLOW

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Abstract

The flow behaviour of SCC is currently being investigated as an ongoing PhD project. This paper presents a development of the Distinct Element Method using the commercial software PFC3D to model the flow of SCC. A good correspondence was obtained between laboratory test and numerical result for the slump flow test.

1. INTRODUCTION

In order to facilitate for the market to fully utilize the high potential of SCC, with its excellent form filling features, a computational tool is under development at the Swedish Cement and Concrete Institute (CBI) to enable a prediction of its flow behaviour [1]. This will increase control over complex situations, which otherwise may lead to poor form filling, surface imperfections and aggregate blocking. A computer simulation of the concrete flow into place in the formwork may serve as an effective tool to reduce or even eliminate these problems. Predictions and advanced problem detection of different casting results would greatly improve product quality and save both time and money.

Various types of software and simulation methods, such as continuous formulations (e.g. Computational Fluid Dynamics, CFD), discrete approaches (e.g. Distinct Element Method, DEM) or a combination of both (particles in liquid), which is quite time and computation demanding, are currently used to simulate concrete flow. Some examples of other simulation methods than DEM, which is presented here, can be found in [2-7].

Using DEM to model individual particles is a convenient approach to simulate and predict physical aggregate blocking. An optimization of the concrete constituents and the amount of aggregate maximizes cost reduction. An increased amount of aggregate is also believed to reduce creep and shrinkage deformation [8]. In the future, numerical design of SCC mixtures with optimized performance relative to the geometry of the formwork, casting technique and configuration of reinforcement could be performed in order to increase production capability and quality.

However, the traditional approach of the DEM software, i.e., modelling individual grains, suffers from the need of an excessive amount of elements to successfully model the fluid phase of concrete, i.e., the paste. This paper takes a closer look at an alternative model, which avoids some of the heavy computational costs combined with a new contact model.
2. NUMERICAL METHOD

2.1 A suitable model of concrete

Fine mortar is a particle suspension where cement, filler and aggregate < 0.25 mm are suspended in water. The same way, mortar may be viewed as a particle suspension where sand is suspended in fine mortar. Similarly, concrete can be regarded as a particle suspension where the coarser aggregate particles are suspended in mortar. Further, one way to save computation time, simulating concrete flow, would be to eliminate particles below a certain size (below a cut-off line), and model only aggregates above that size. Adjusting the viscosity of the paste and remaining aggregates to an adequate level may maintain the flow behaviour of the concrete, and still, if adequate, show blocking. Simplifying the model of concrete as much as possible will ensure simulations of larger volumes at faster computation rates.

2.2 The Distinct Element Method

The Distinct Element Method, DEM, was first introduced in 1971 by Cundall [9]. The modelled material is treated as a finite set of discrete elements, or particles. Each individual particle moves according to:

\[ F = m \cdot a \]  
\[ M = I \cdot \omega \]  

Where \( F \) = force [N], \( m \) = mass [kg], \( a \) = acceleration [m/s^2], \( M \) = torque [Nm], \( I \) = moment of inertia [kg m^2] and \( \omega \) = angular acceleration [rad/s^2]. By defining the interactions between individual particles, a macroscopic behaviour of the material is established. Identifying the nature and magnitude of the inter-particle interactions is not trivial, implying that a thorough study of parameters is necessary. The DEM Software PFC3D was used to obtain the results presented here and it is classified as a discrete element code since it allows displacements and rotations of the particles, including complete detachments. All particles used are spherical and contacts between particles occur over an infinitely small area, a point. Different shapes of aggregate may be simulated by merging several particles together as one, forming a so-called super-particle [9].

2.3 Contact constitutive models

Contacts between particles may be rigid or loose and they may break and reform. For particles establishing contact, three different models, or numerical components, are to be found in the PFC3D “toolbox”.

![Figure 1: The PFC3D toolbox for ball to ball or ball to wall contacts consists of spring, dashpot and slip, which cuts off all forces above a certain level](image-url)
2.4 Different approaches to model concrete

The two phases, the liquid phase mortar and the solid phase aggregates, may be represented in different ways using DEM. In [10] the mortar phase is represented as individual mortar particles, having different contact parameters from the aggregates. This approach may require a very large amount of particles, combined with a risk of an unwanted separation of the two phases due to differences in density between the two particle types. A different approach is suggested in [11], where each particle is a piece of rock enclosed by a paste layer, i.e., a paste particle completely surrounding a hard aggregate core.

2.5 The Bingham contact model

A Bingham material behaves elastically below the yield stress level and displays a linear viscous behaviour above the yield stress in the shear plane.

![Bingham material model](image)

Figure 2: A Bingham material may be described in terms of a spring, dashpot and slip [12]

According to [12], a Bingham model may be pictured in terms of spring, dashpot and slip function (Figure 2).

If shear stress acts between the particles, most of the stress would be supported by the spring, ensuring an elastic behaviour. At the yield stress limit, slip occurs and the elastic stress of the spring is maintained at constant value. Above the yield stress, any additional force is due to viscosity (the dashpot).

The above-presented approach was used in PFC3D to model the mortar phase of concrete as a Bingham material. In addition to the Bingham model acting in the tangential direction, contact has also been defined in the normal direction for mortar (Figure 3).

![Contact model in the normal direction](image)

Figure 3: Contact model in the normal direction for mortar phase
A non-linear spring has been introduced in order to model the attractive forces (e.g. liquid bridges) between particles in the normal direction. Information on forces acting between particles may be found in [13], originating from [14]. At particle overlap, repulsive forces increase linearly. Attractive forces between particles vanish at $x_{\text{stop}}$ (Figure 3) corresponding to the characteristic radius of the interacting particles. The characteristic radius of two particles with a radius of $r_1$ and $r_2$ respectively, is evaluated as:

$$r_c = 2 \cdot \frac{r_1 \cdot r_2}{r_1 + r_2} \quad (3)$$

Shear force during tension is computed using the Bingham model, however, the force decreases as distance increases, using the following multiplicative correction factor:

$$\frac{1}{1 + 100 \cdot \left(\frac{x_{\text{stop}} - x}{x_{\text{stop}}}\right)} \quad (4)$$

The Bingham model is applied to the paste layer of each particle. The hard rock inside the layer has been given different material parameters. The core is assumed to be non-deformable and experiences friction when scraping occurs. It is possible for aggregates to “get stuck” next to a wall or reinforcement bar. This way, blocking may be modelled in the simulations.

2.6 Particle size distribution

The modelled particle size distribution is represented by the actual grading curve. The cut-off line between the aggregate and the mortar phase is here set to 2 mm. In order to speed up computations, the cut-off line could be moved upwards towards greater particle size, further decreasing the amount of particles as the model becomes more simplified.

3. RESULTS

The rheology of an SCC, measured with a Contec-4 SCC viscometer, was according to the Bingham model equal to a yield stress $\tau_0$ of 30 Pa and a plastic viscosity $\mu_p$ of 72 Pa·s. The correspondence between laboratory tests and numerical simulation is good (Figure 4).

Figure 4: Slump flow values of the simulation and video recording (left) and the final spread showing a nicely rounded and homogeneous concrete slump flow (right)
The numerical results were obtained by selecting the set of parameter values below. Please note that contact properties are particle size dependent and that Equation (3) applies, as shown in Table 2. The amount of particles used for the slump flow simulation is approximately 24000. The radius ratio gravel to full particle size is 1.4175. Faster computations are possible for a rheologically equivalent behaviour of the simulated concrete by moving the cut-off line (shown in Table 2) upwards, decreasing the amount of particles to approximately 3100. Contact parameters and the paste content, defined by the radius ratio gravel to full particle size, would have to be adjusted accordingly.

Table 1: Contact parameters illustrated in Figure 2 and 3 used in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aggregate</th>
<th>Mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_n$</td>
<td>$8.6 \cdot 10^6 \cdot r_c$</td>
<td>$2.94 \cdot 10^3 \cdot r_c$</td>
</tr>
<tr>
<td>$d_p$</td>
<td>$4.33 \cdot 10^5 \cdot r_c^2$</td>
<td>$4.5 \cdot 10^4 \cdot r_c^2$</td>
</tr>
<tr>
<td>$k_s$</td>
<td>$3.62 \cdot 10^4 \cdot r_c$</td>
<td>$2.94 \cdot 10^1 \cdot r_c$</td>
</tr>
<tr>
<td>$d_p$</td>
<td>$5.61 \cdot 10^3 \cdot r_c^2$</td>
<td>$1.5 \cdot 10^2 \cdot r_c^2$</td>
</tr>
<tr>
<td>Slip (corresponding to $\tau_0$)</td>
<td>N/A</td>
<td>1.5 \cdot r_c^2</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.4</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 2: Numerical aggregate size distribution corresponding to actual grading curve

<table>
<thead>
<tr>
<th>Size fraction [mm]</th>
<th>Representative Radius [mm]</th>
<th>% of weight</th>
<th>Number of part. inside cone</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 – 16</td>
<td>7.5625</td>
<td>17.142</td>
<td>316</td>
</tr>
<tr>
<td>11.2 – 12.5</td>
<td>6.0875</td>
<td>3.86</td>
<td>136</td>
</tr>
<tr>
<td>10.0 – 11.2</td>
<td>0.5450</td>
<td>5.032</td>
<td>248</td>
</tr>
<tr>
<td>8 – 10</td>
<td>0.0475</td>
<td>4.905</td>
<td>365</td>
</tr>
<tr>
<td>4 – 8</td>
<td>0.3500</td>
<td>11.145</td>
<td>2073</td>
</tr>
<tr>
<td>2 – 4</td>
<td>0.1750</td>
<td>14.088</td>
<td>20961</td>
</tr>
<tr>
<td>1 – 2</td>
<td>N/A</td>
<td>13.047</td>
<td>N/A</td>
</tr>
<tr>
<td>0.5 – 1</td>
<td>N/A</td>
<td>11.390</td>
<td>N/A</td>
</tr>
<tr>
<td>0.25 – 0.5</td>
<td>N/A</td>
<td>9.181</td>
<td>N/A</td>
</tr>
<tr>
<td>0.125 – 0.5</td>
<td>N/A</td>
<td>6.167</td>
<td>N/A</td>
</tr>
<tr>
<td>0.063 – 0.125</td>
<td>N/A</td>
<td>1.695</td>
<td>N/A</td>
</tr>
<tr>
<td>&lt;0.063</td>
<td>N/A</td>
<td>2.349</td>
<td>N/A</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

- The slump flow is accurately modelled using the above described model. It describes the rheology of the concrete correctly; the geometry and timing of the video recorded slump coincide with the simulation.
- The model allows versatility with possibilities to define different contact parameters for different parts of the model/particle.
- As can be seen in Figure 4 (right), the different aggregate fractions are evenly distributed throughout the slump; this approach is well suited to model inhomogeneous matter in a stable way.
This model serves as a foundation for further parameter studies, since contact parameters are particle size dependent and an obvious correlation between Bingham parameters and the numerical parameters are not easy to find.

Different geometries and SCC’s with different rheology will be further investigated, using this DEM model.

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REFERENCES