SIMULATING THE WORKABILITY OF FRESH CONCRETE

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Abstract

This paper proposes a numerical approach based on the Distinct Element Method (DEM) as a means of fresh concrete simulation during its different working processes. A rheological model for concrete in a fresh state was developed and implemented in a DEM code. An extensive study followed to investigate the effect of various model parameters on the results of the numerical simulation of the slump test. The calculation results were discussed with regard to the correct choice of values for the model parameters as required for a realistic description of specific material behaviour.

INTRODUCTION

In concrete construction many problems result from the improper filling of formwork, insufficient de-airing, concrete segregation, etc. The importance of this issue has increased year after year since formwork is becoming continually more and more complex. Steel reinforcement has become denser, and the range of workability has been considerably broadened by the use of Self-Compacting Concrete (SCC). In order to carry out concrete construction efficiently and with high quality, the consistency of fresh concrete should comply with the requirements posed by the structure geometry and methods of transport, placing and compaction. Computer simulation of fresh concrete behaviour and the working processes could provide a powerful tool in optimizing concrete construction and developing new concrete technologies.

Previous publications by the authors [1, 2] showed that the Particle Method, which is a variation of the Distinct Element Method, provides a good basis for the continuous modelling of concrete behaviour during the working process, the hardening process, and, subsequently, in the hardened state. It was found that the simulations provided qualitatively sound results in principle, displaying decisive phenomena correctly, as observed in corresponding experiments.

The purpose of this paper is the identification of the model parameters for the simulation of fresh concrete as a first step towards a reliable quantitative analysis of the working processes. An extensive parameter study was performed in order to provide an overview of the effects of individual model parameters on the results of a widely used standard test (Slump/Slump flow test), while regarding fresh concrete as a homogeneous material.
PARTICLE METHOD

Particle Flow Code ITASCA was used in this investigation as a basic program [3], which enables the modelling of the movement (translation and rotation) of distinct particles, including their interactions as well as their separation and automatic contact detection [4]. The interaction between individual particles in contact with one another is defined by constitutive relations. In contrast to a more general DEM, only two basic elements are used in the particle method: circular particles with a unit thickness (2D simulations) or spherical particles (3D simulations) and walls. In this investigation circular or spherical particles, depending on the number of dimensions chosen, were used to discretise concrete, while walls were utilized in simulating the boundaries.

The particles themselves are defined to be rigid. Their interaction is treated as a dynamic process with a developing state of equilibrium whenever the internal forces are in balance. The contacts between neighbouring particles occur only at one point at a given time. The calculations alternate between the application of Newton’s Second Law with respect to the motion of particles and the force-displacement law at the contacts. The Newton’s law is used to determine the motion of each particle arising from the contact and the forces acting upon it as a body. The dynamic behaviour is represented numerically by a time-stepping algorithm which assumes that the velocities and accelerations are constant within each time step. The force-displacement law is then used to update the contact forces arising from the relative motion at each contact. This process is based on the resultant force and moment arising from the contact forces and any other body force, e.g., gravity, acting on the particle.

The contact force vector \( F_i \), which represents the action of particle A on particle B in particle-to-particle contact, and represents the action of the wall on the particle for wall-to-particle contact, can be resolved into its normal and shear components with respect to the contact plane according to Eq. 1:

\[
F_i = F_i^n + F_i^s
\]

where \( F_i^n \) and \( F_i^s \) denote the normal and shear component vectors, respectively.

The force-displacement law relates these two force components to the corresponding components of the relative displacement.

The library of the Particle Flow Code contains only very simple constitutive relations for the interaction between particles [3], but this is not sufficient to simulate the rheological behaviour of fresh concrete satisfactorily. For this reason the authors developed their own models as described in the following Chapter.

RHEOLOGICAL MODEL

Fresh concrete can be considered as a suspension roughly described by two rheological parameters, yield stress and plastic viscosity, according to Bingham’s model, Eq. 2. In this model, the yield stress \( \tau_0 \) gives the upper limit for the static behaviour of the materials, and the plastic viscosity \( \eta \) relates to its dynamic response.

\[
\tau = \tau_0 + \eta \cdot \dot{\gamma}
\]
where $\tau$ is the shear stress and $\dot{\gamma}$ is the shear rate.

Constitutive relations based on the Bingham formula were developed by the authors and implemented into the Particle Flow Code in order to describe the interactions between two neighbouring particles for simulating fresh concrete. The corresponding rheological models for the normal and tangential direction are shown in Figure 1. They consist of the basic rheological elements spring, dash-pot, and slider, which respectively represent the elastic, viscous and friction components of the particles interaction.

The interaction model includes also the element “contact” positioned serially in line with the basic rheological elements. This additional element enables the definition of the strength of the contact, the simulation of the loss of an old interaction due to the reaching of a certain distance between two particles, and the formation of a new interaction. Figure 2 shows schematically two types of force-displacement relations as introduced by the authors for the contact elements in the normal direction and subsequently used in the numerical investigations.

The first version (CM1) of the force-displacement law in the normal direction includes two main modes: compression and tension (cf. Figure 2). The compression mode is defined by a fixed value of stiffness, while the force-displacement curve in tension mode linearly ascends to a defined ultimate force (the bond strength) and then linearly decreases down to zero in a kind of softening regime. When the tensile force becomes zero, the particles lose contact.
Since model CM1 for the particle interaction in the normal direction does not include frictional elements (cf. Figure 1, left), the modelling of the characteristic behaviour of fresh concrete related to the yield stress $\tau_0$ might not be accurate enough if the force-displacement relation as described in the previous paragraph is used. Therefore, a slightly modified contact model CM2 was proposed as an alternative. The contact between neighbouring particles in tension is defined at small deformations by a very steeply ascending branch, i.e., there is practically no deformation until a given force value (here “yield force”) is reached. After reaching this force level there is only a slight increase in tensile force while the corresponding deformations increase rapidly. The descending branch of the force-displacement relation does not defer from that of the model CM1.

**PARAMETER STUDY**

**4.1 General remarks**

Previous investigations showed that it is possible to simulate the effect of concrete composition on its rheological behaviour by defining the components of the concrete mesostructure (fine mortar, coarse aggregates, fibres) discretely [2]. In this parameter study a different approach was chosen. The concrete should be simulated using particles of only one size at a time. In this way the effects of the different model parameters should be more recognisable. Such a numerical model with one-size particles can be interpreted as a multitude of round (or spherical) aggregate grains of some “average”, representative size, each uniformly covered by a layer of cement paste (or fine mortar). It should be mentioned here that the assumption of a single particle size has clear advantages with regard to the prospective practical application of the numerical approach presented, since such a discretisation of concrete is simple and the corresponding calculations are very fast.

The parameters to be investigated can be subdivided into two categories. The first category relates to the properties of individual particles such as size, density and stiffness. Furthermore, the choice of 2- or 3-dimensional discretisation results in two different shapes of particles, i.e., disks or spheres, respectively. The second category includes all the parameters which define the interaction between the particles. These parameters are the stiffness and the coefficients of friction and viscosity as well as the shape of the force-displacement relations in the normal direction. The last parameter determines first of all the strength of the bond and the value of the “yield force” should the model CM2 be used.

The sequence of the parameters as presented in the following sub-chapters results from the logical succession of the choices to be made. To begin with, an appropriate particle size must be chosen. In doing this naturally the maximum aggregate size of concrete should be considered as well as the geometrical data of the boundaries (e.g., the size and shape of the formwork). Since no special consideration of some particular concrete compositions was aimed at in this study, the limits for the choice of the particle sizes were provided by the geometry of the “virtual testing equipment” used, i.e., the Abraham’s cone.

The density of the particles provides the definitive value for the calculation of particle actions due to gravity. In the case of the slump test as simulated in this investigation, gravity is the only operating force in the system. The density equal to 2.3 kg/dm³ was assigned to all the particles in parameter study performed, simulating ordinary, normal-weight concrete as a homogenous mass.
Since the particles are considered to be rigid bodies in the calculation, their stiffness is infinite, both in the compression and tension modes. The finite stiffness of the virtual concrete results from the definition of elastic properties for the interaction between the particles. In doing this, concrete was considered as nearly uncompressible material, it means that the particles under compression would have only a minimal overlap.

The parameters of the second category, i.e., those defining the interaction between the particles, are important to the simulation of concretes with different rheological properties. The aim of the parameter study was to identify quantitatively the effects of the individual parameters. On this basis an algorithm should be developed for a purposeful choice of their combinations in order to arrive best at the behaviour of a particular fresh concrete.

The slump test was simulated over and over in this parameter study. Key data, i.e., slump value, slump flow diameter (for concretes with a soft consistency) and the time of spreading, was determined as if in actual tests. Numerous previous experimental studies showed how these properties relate to the rheological parameters of fresh concrete. This paper helps to establish links between the model parameters and the experimentally obtained key values.

### 4.2 Effect of the particle size and the dimension of modelling (2D or 3D)

The use of small particle sizes is limited by long calculation times resulting from a great number of the particles per unit volume, the maximum size by the characteristic aggregate size, which should be smaller than the maximum aggregate size of the concrete under consideration. Table 1 shows the results of the 2D and 3D simulations of the slump test using particle size of 5 mm, 7 mm and 10 mm, respectively, while all the other parameter of the model remained unchanged. A change in the particle size evidently leads to an alteration of the mechanical interaction between particles and, as a result of it, to a pronounced effect on the rheological behaviour of simulated concrete. Larger particles size corresponds to higher values of the slump and the slump-flow diameter.

Table 1: Effect of particle size on the results of the simulated slump test

<table>
<thead>
<tr>
<th>Particle diameter and the image of the “concrete cake” at the end of simulation</th>
<th>Calculation data</th>
<th>Calculation data</th>
<th>Particle diameter and the image of the “concrete cake” at the end of simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2D simulation</strong></td>
<td><strong>3D simulation</strong></td>
<td><strong>2D simulation</strong></td>
<td><strong>3D simulation</strong></td>
</tr>
<tr>
<td>5 mm</td>
<td>Number of particles: 3254</td>
<td>Number of particles: 51551</td>
<td>5 mm</td>
</tr>
<tr>
<td>Slump: 12 cm</td>
<td>Slump: 12 cm</td>
<td>Slump: 12 cm</td>
<td></td>
</tr>
<tr>
<td>Slump flow: 37 cm</td>
<td>Slump flow: 35 cm</td>
<td>Slump flow: 35 cm</td>
<td></td>
</tr>
<tr>
<td>7 mm</td>
<td>Number of particles: 1546</td>
<td>Number of particles: 18512</td>
<td>7 mm</td>
</tr>
<tr>
<td>Slump: 13 cm</td>
<td>Slump: 13 cm</td>
<td>Slump: 13 cm</td>
<td></td>
</tr>
<tr>
<td>Slump flow: 41 cm</td>
<td>Slump flow: 37 cm</td>
<td>Slump flow: 37 cm</td>
<td></td>
</tr>
<tr>
<td>10 mm</td>
<td>Number of particles: 624</td>
<td>Number of particles: 6491</td>
<td>10 mm</td>
</tr>
<tr>
<td>Slump: 20 cm</td>
<td>Slump: 20 cm</td>
<td>Slump: 20 cm</td>
<td></td>
</tr>
<tr>
<td>Slump flow: 50 cm</td>
<td>Slump flow: 50 cm</td>
<td>Slump flow: 50 cm</td>
<td></td>
</tr>
</tbody>
</table>
This effect can be traced back to the fact that larger particles are heavier, i.e. the gravity force acting at each large particle is higher in comparison to the case when small particles are used. Since all the parameters describing the interaction between particles remain unchanged, the balance between the acting force and the resistance to the movement changes in favour of higher displacements. This means that with increasing particle size the parameters of the particle interaction should be adjusted in order to obtain the same simulation result in terms of slump and slump-flow values.

It should be noted that the use of particles with a diameter 2.5 mm (not presented in Table 1) did not show a pronounced change in the simulation results in comparison to the calculation in which a diameter of 5 mm was used. Hence, the effect of particle size fades when the particle size becomes smaller.

A comparison of the calculated images for the “concrete cake” at the end of simulation as shown in Table 1 shows that the dimension of modelling does not significantly affect the obtained results. This is good news since a two-dimensional analysis is easier and faster and thus would be the first choice if the accuracy of the numerical simulation is comparable to that of the three-dimensional analysis.

All results presented in the following chapters were obtained for particles 7 mm in diameter.

4.3 Effect of bond strength in the contact model

The value of the bond strength $bond$ in the contact model is the determining factor in the interaction between neighbouring particles. When the tensile force reaches this value, the force-displacement relation shifts to the softening regime, and as a rule contact will be gradually lost. Therefore, it is not surprising that this parameter has a dramatic effect on the results of the simulation, cf. Figure 3. In changing the value $bond$ by a factor of 100, the calculated response of the numerical concrete changes from a kind of “self-compacting concrete” (slump flow of 60 cm) to “stiff ordinary concrete” (no slump flow). Considering such pronounced effect as well as the physical meaning of the parameter $bond$, this parameter seems appropriate to determine the type of virtual concrete.
4.4 Effect of the ascending branch in the contact model

Figure 4a shows a rather typical deformation state of a concrete “cake” resulting from slump tests with the Abraham’s cone. The shape of the upper part of the “cake” remains practically unchanged, while the lower part is deformed under the action of the concrete own weight. A clear transition between the deformed and non-deformed regions of the “cake” can be observed. This transition results from reaching the yield force at the given height of the “cake” due to the action of the gravity force.

The simulation using the contact model CM1 with a linearly ascending branch of the force-deformation relation cannot provide the response for the virtual concrete described: Figure 4b shows a smooth, “smeared” transition between non-deformed and clearly deformed regions. By using the contact model CM2 with a given yield force value a much sharper transition could be obtained, similar to that from the experiments (cf. Figure 4c). In this simulation the yield force value was set at 90% of the bond strength value \( \text{bond} \).

4.5 Effect of friction and viscosity

The effect of the parameter \( \text{fric} \), which represents the yield stress of concrete in the shear direction and is manifested in the rheological model by the friction element “slider”, is demonstrated in Figure 5. An increase of the \( \text{fric} \) value by a factor of 10 leads to a decrease of the calculated slump flow diameter by 7 cm. Remarkably, a further increase in \( \text{fric} \) by a factor of 10 or 100 results again in a decrease in the slump flow diameter by 7 and 14 cm, respectively.

\[
\begin{align*}
\text{fric} = \text{fric}_0 & \quad \text{Slump flow 67 cm} \\
\text{fric} = 10\times\text{fric}_0 & \quad \text{Slump flow 60 cm} \\
\text{fric} = 100\times\text{fric}_0 & \quad \text{Slump flow 53 cm} \\
\text{fric} = 1000\times\text{fric}_0 & \quad \text{Slump flow 46 cm}
\end{align*}
\]
When the particles start to move, the dashpot parameter $c_s$ representing the viscosity of the material comes into action. This parameter can be independently set for both shear and normal directions. However, in this study the same values were used for both these directions. It was found that the parameter $c_s$ influences the time of calculation only. The shape of the virtual concrete “cake” at the end of the simulation was the same, independent of this parameter. An increase of the value $c_s$ by three times, when simulating “self-compacting concrete”, caused a nearly proportional increase of the program calculation time from 48 seconds to 167 seconds.

CONCLUSIONS

A model for the simulation of rheological behaviour of fresh concrete was developed in the frame of the Distinct Element Method. Subsequently, a parameter study was performed in order to quantify the effects of individual parameters of the model on the results of the numerical simulation of the slump test with Abraham’s cone. The analysis of the obtained results provided a basis for first considerations concerning an algorithm for the choice of the model parameters, when concretes with various rheological properties must be simulated.

It seems advantageous to start setting the parameters by choosing an appropriate particle size. In doing this, a representative size of the aggregates can serve as a reference measure. A particle size between 1/3 and 1/2 of the maximum aggregate size can be recommended at this stage, if particles of only one size are used.

The bond strength $bond$ should be chosen in the second step, since it is the main parameter for characterising the interaction of the neighbouring particles. The $bond$ value must be set according to the type of concrete to be simulated (stiff ordinary concrete, SCC etc.).

The fine-tuning of the model is performed by adjusting the parameters $fric$ and $c_s$, which are related to the rheological properties “yield stress” and “plastic viscosity” according to the Bingham model, respectively. The friction parameter $fric$ can be calibrated on the final slump or slump flow diameter from the tests with the Abraham’s cone. For reasons which are specific for the DEM analysis with round or spherical particles, it is helpful, but not mandatory, to use here for the normal direction the contact model CM2, which contains an additional parameter “yield force”. This parameter just affects the shape of the transition region from the non-deformed to the deformed part of the concrete “cake” but does not influence the slump or slump flow values. The parameter $c_s$ has an effect on the computation time only, which can be related to the spreading time in the slump flow test on flowable or self-compacting concrete.

Ongoing investigations will provide further information on the possibilities and limitations of the simulation of fresh concrete behaviour using the developed model.

REFERENCES
