Blocking Mechanism Study of Self-Compacting Concrete Based on Discrete Element Method

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Abstract. In order to study the influence factors of blocking mechanism of Self-Compaction Concrete (SCC), Roussel’s granular blocking model was verified and extended by establishing the discrete element model of SCC. The influence of different parameters on the filling capacity and blocking mechanism of SCC were also investigated. The results showed that: it was feasible to simulate the blocking mechanism of SCC by using Discrete Element Method (DEM). The passing ability of pebble aggregate was superior to the gravel aggregate and the passing ability of hexahedron particles was bigger than tetrahedron particles, while the tetrahedron particle simulation results were closer to the actual situation. The flow of SCC as another significant factor affected the passing ability that with the flow increased, the passing ability increased. The correction coefficient $\lambda$ of the steel arrangement (channel section shape) and flow rate $\gamma$ in the block model were introduced that the value of $\lambda$ was 0.90-0.95 and the maximum casting rate was 7.8 L/min.

1. Introduction
In recent years, with rapid development and extensive application of SCC, more and more construction projects are beginning to use SCC. In some special conditions, such as coarse aggregate size large or reinforced configuration too dense, it may still happen blocking phenomenon and not fill with lead to structure within the dense area [1]. Many scholars have conducted the slump or slump flow to study the relationship between the yield stress of concrete, measured slump or slump flow is determined by material yield stress, and has nothing to do with the plastic viscosity [2]. Khayat [3] adopted slump flow test, V-funnel test and filling capacity test (parallel steel, spacing is 34mm) to study fiber reinforced SCC and showed that V-funnel test and filling capacity test had no special relationship. Xie [4] used Multi-scale method to study the filling capacity of SCC, it was concluded that application scope of these two models and studied affect of the stone size, mortar flow to filling capacity.

Compared with numerical simulation and laboratory test, it can save a lot of manpower and material resources and financial resources, which can effectively avoid error caused by the test conditions, personnel, operating and experimental environmental factors. A large number of researchers have started to adopt the method of numerical calculation was carried out on the concrete simulation studies [5]. Numerical methods mainly include Discrete Element Method (DEM) [6], the Lattice Boltzmann Method (LBM) [7], Computational Fluid Dynamics (CFD) [8], Smoothed Particle Hydrodynamics (SPH) [9] and so on, among them, the Discrete Element Method can be used for simulating the macro flow state of concrete, but also in the process of flow within the aggregate particles collide with each other between the friction phenomenon. Puri [10] applied a combination unit of mortar wrap the aggregate particles to simulate concrete, and made a 2D simplified simulation of the relationship between the injection pressure and the rebound quantity of the shotcrete. SCC was also simplified as coarse aggregate and mortar units, the slump, V-funnel and the U-box experiment of
SCC were simulated [11]. A new DEM model for the simulation of SCC flow was presented that it was described as an assembly of composite particles made of spherical hard grains representing coarse aggregates surrounded by concentric spherical layers representing mortar, rheological simulations showed that the rheological behavior of simulated concretes can be approximated with the Bingham model [12]. Mechtcherine [13] used DEM define the rheological model of SCC, then the main focus was directed at establishing an algorithm to derive the model parameters related to yield stress according to the Bingham model, the results of the numerical analysis agreed well with the results predicted by analytical solutions for all parameter combinations. Huang [14] conducted a quick contact searching algorithm of HACell and the DEM constitutive model of self-compacting mortar (SCM) and SCC, the rheological parameters of SCM element were used in the simulation of flow ability and viscosity of SCM.

In this paper, SCC is simplified as the coarse aggregate and the mortar two-phase medium, a 3D DEM model for SCC is established and validated and the rheological model adopts the Bingham model, then Roussel’s granular blocking model is verified and extended by establishing the discrete element model of SCC and the influence of different parameters on the filling capacity and blocking mechanism of SCC are also investigated.

2. Discrete element model of SCC

The discrete element method is a method to simulate rigid ball movement and interaction based on discrete element theory. A fundamental assumption of this method is that the material consists of separate discrete particles and the particles are treated as rigid bodies. The contacts between neighboring 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. Thus the displacements and rotations of the particles are calculated according to the following governing equations (1) and (2).

\[ F_i = m \cdot (\ddot{x}_i - g_i) \]  
\[ M_i = I \cdot \omega_i \]  

where \( F_i \) is the resultant force, \( m \) is the total mass of the particle, \( \ddot{x}_i \) is the translational acceleration and \( g_i \) is the acceleration of gravity. \( M_i \) is the resultant moment acting on the particle, the moment of inertia \( I \) and the angular acceleration of the particle \( \omega_i \).

The contact force vector \( F_i \) which represents the action of ball-ball contact, and the action of the ball on the wall for ball-wall contact can be resolved into normal and shear components with respect to the contact plane according to equation (3).

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

where \( F_i^n \) and \( F_i^s \) denote the normal and shear component vectors, respectively. The contact stiffnesses relate the contact forces and relative displacements in the normal and shear directions via equations (4) and (5), which are repeated here.

\[ F_i^n = K^n U^n n_i \]  
\[ \Delta F_i^s = -k^s \Delta U_i^s \]  

where \( K^n \) and \( k^s \) denote the normal and shear stiffness, \( U^n \) and \( \Delta U_i^s \) denote the normal and shear relative displacement at the contact, \( n_i \) denotes the normal vector of contact plane.

Concrete is a composite material composed of a variety of materials. In the discrete element simulation, it is obviously not realistic to use a variety of particles to simulate the various materials of
concrete. This article summarizes the research results of scholars, the SCC is simplified as two phases of coarse aggregate and mortar, respectively used two kinds of particles with different materials properties. The mortar is treated as a kind of discrete element which used parallel bond model, and coarse aggregate is treated as another kind of discrete element which used linear contact model, the discrete element model of SCC is established by adding different contact relations.

3. Rheological model of SCC
Concrete can be considered as a fluid, provided that a certain degree of flow can be achieved and that the mix is quasi-homogeneous with regularly dispersed aggregate particles. There are many models describing the rheological properties of concrete, Bingham model Herschel-Bulkley model are best suited to the real situation [15, 16]. Bingham model consists of Newton fluid model and St. Venant solid model, rheological equation is given by equation (6).

\[ \begin{cases} \tau = \tau_0 + \mu_p \dot{\gamma} & |\tau| > \tau_0 \\ \dot{\gamma} = 0 & |\tau| < \tau_0 \end{cases} \]  

where \( \tau_0 \) is the yield stress, \( \mu_p \) is the plastic viscosity and \( \dot{\gamma} \) is the shear rate. Both of these two models contain two key parameters: \( \tau_0 \) and \( \mu_p \). \( \tau_0 \) is the maximum internal force of material internal resistance to plastic deformation, it is caused by adhesion and friction force between each phase, and determines the deformation of the material, has nothing to do with the external factors. \( \mu_p \) is a characteristic that prevents its shear deformation from inside the material. It represents the resistance of the flow of the material which the flow layers to prevent its flow and determines the velocity of the material flow.

4. Study on passing ability and blocking mechanism of SCC
The French scholar Roussel proposed the granular blocking model of SCC, it is verified and extended by establishing the discrete element model of SCC and the influence of different parameters on the filling capacity and blocking mechanism of SCC are also investigated. The blocking parameter \( P \) applicable to concrete was obtained to predict the probability that the concrete would be blocked by obstruction.

\[ P = (2.6\Omega / D_{\text{max}}^3)(0.1\phi)^{0.85\delta^2/0.81(\beta D_{\text{max}})^2} \]  

where \( D_{\text{max}} \) is the diameter of the coarsest particles, \( \phi \) is the volume fraction of the aggregate particles, \( \Omega \) is the total amount of concrete, obstacle spacing \( \delta \) and coarse aggregate shape \( \beta \).

**Figure 1.** Schematic of model size.  **Figure 2.** Final shape of slump flow 500×500mm.

4.1. Building of model
Based on literature [4] to establish a model size as shown in figure 1. In order to study the different parameters on the properties of SCC through the influence of test selection flow (690×690mm, 550×550mm), coarse aggregate size (5-10mm, 5-20mm), shape of coarse aggregate (gravel, pebble),
steel spacing (20-40mm) and casting rate (1.5-4L/min) as the main parameters. Simulation results compare with the literature [4] test results analysis the blocking mechanism of SCC. The mixture ratio and parameter information of SCC used in simulation test are shown in table 1.

**Table 1. Mixture ratio of SCC.**

| Group number | C (Kg) | W (Kg) | S (Kg) | G (Kg) | Type | Distribution (mm) | Slumpflow (mm) |
|--------------|--------|--------|--------|--------|------|-------------------|----------------|
| No. 1        | 491    | 205    | 859    | 694    | gravel | 5-20              | 690×690         |
| No. 2        | 491    | 205    | 859    | 694    | gravel | 5-20              | 550×550         |
| No. 3        | 491    | 205    | 859    | 694    | gravel | 5-10              | 690×690         |
| No. 4        | 491    | 205    | 859    | 694    | pebble | 5-10              | 690×690         |

4.2. Calibration of microscopic parameters

Particles microscopic parameters will directly affect macroscopic rheological properties of SCC. However the microscopic parameters between particles cannot be directly obtained through macroscopic mechanical tests such as laboratory tests, and can only be obtained through numerical tests. According to the slump flow of table 1, slump simulation test is carried out on microscopic parameters (figure 2) preliminary Calibration, the simulation tests debug repeatedly and reference literature [13], checking to calculate different slump flow microscopic parameters of SCC, microscopic parameters of slump flow 500×500mm are shown in table 2.

The simulation is carried out according to distribution curve of the literature [4]. The distribution curve is shown in figure 3, the slump simulation used the same distribution curve. Due to the influence of discrete element calculation efficiency, it is impossible to calculate relatively small particles. Therefore, it is possible to treat the part that is less than 4.75mm as an aggregate (4.75mm) to process the mortar of SCC. The coarse aggregate and mortar materials are simulated with different radius spherical particle, and the coarse aggregate particles generated by the middle limit of distribution are 553, and the mortar particles are 5247.

![Figure 3. The distribution curve of mixed aggregate.](image)

**Table 2. Parameters of parallel bond model (550×550mm).**

| Parameters                  | Aggregate-Aggregate | Aggregate-Mortar | Mortar-Mortar |
|-----------------------------|---------------------|------------------|---------------|
| Normal strength (N·m⁻¹)     | ×                   | 4×10⁴            | 4×10³         |
| Shear strength (N·m⁻²)      | ×                   | 2×10⁴            | 3×10³         |
| Normal stiffness (N·m⁻¹)    | ×                   | 1×10⁴            | 2×10³         |
| Shear stiffness (N·m⁻²)     | ×                   | 5×10³            | 1.5×10³       |
| Bond radius                 | ×                   | 0.35             | 0.25          |
| Local damping               | 0.70                | 0.70             | 0.70          |
5. Discrete element numerical simulation and analysis

5.1. Effect of steel spacing

Effect of changing the steel spacing on SCC shows in table 3. With the decrease of steel spacing, the passing ability of SCC decreases gradually to 30% after the steel spacing is less than 30 mm, it has a serious blocking phenomenon that could not satisfy the filling requirement. Blocking probability $P$ also shows the same trend. It can be seen from the comparison between physical test and simulation test that it is feasible to use discrete element to simulate the passing ability of SCC. Figure 4 shows the different situation diagram of the model when the steel spacing is 20mm, initial situation (figure 4(a)) and final situation (figure 4(b)) of model, the local illustration (figure 4(c)) near the steel are shown. The main reason for the blocking is the accumulation of coarse aggregate in the vicinity of the steel, with the passing of mortar particles, coarse aggregate particles gradually accumulate near the steel and size of coarse aggregate is greater than that of the steel spacing, and the blocking of natural formation is consistent with the actual experiment.

![Figure 4](image)

(a) Initial situation  (b) Final situation  (c) Local illustration of final situation

**Figure 4.** Different situation diagram of steel spacing 20mm.

**Table 3.** Test results of changing steel spacing.

| Test number | SCC number | Steel spacing (mm) | Steel arrangement | Passing ability test/simulation (%) | Parameter $P$ test/simulation |
|-------------|------------|--------------------|-------------------|-------------------------------------|------------------------------|
| 1-1         | No. 1      | 40                 | parallel          | 100/100                             | 0.0006/0.0042                |
| 1-2         | No. 1      | 35                 | parallel          | 100/100                             | 0.02/0.06                    |
| 1-3         | No. 1      | 30                 | parallel          | 76.6/81.5                           | 0.4/0.8                      |
| 1-4         | No. 1      | 25                 | parallel          | 25.1/23.7                           | 4.9/3.8                      |
| 1-5         | No. 1      | 20                 | parallel          | 8.2/10.5                            | 39.6/42.4                    |

5.2. Effect of steel arrangement

Figure 5 shows different arrangement forms of steel spacing 30mm, three groups of steel arrangement (2-1 & 2-2, 2-3 & 2-4, 2-5 & 2-6) were compared with physical test and simulation test (table 4). For the SCC, if parallel steel changes to grid steel, the passing ability of SCC is significantly reduced, the passing ability of grid steel significantly lower than the parallel steel. In the verification test, Roussel [1] used parallel steel and did not discuss the situation of grid steel. To the application of comprehensive Roussel particles blocking model, steel arrangement (channel section shape) correction coefficient $\lambda$ is introduced into parameter $P$, to reflect the steel arrangement way of particles blocking probability, the influence of steel spacing into $\lambda \delta$ at this time, the particles blocking model formula is:

$$P = \left( \frac{2.66 \omega}{D_{\text{max}}} \right)^3 (0.1p)^{0.85(\lambda \delta)^2} \left(0.81(\beta D_{\text{max}})^2 \right)^2$$

(8)

According to the physical test result, the value $\lambda$ was given in 0.87 to 0.97 [4], considering the concrete test generally have larger randomness and discreteness, in order to accurately determine the value of $\lambda$ and develop the advantage of discrete element numerical simulation. After several other groups of numerical simulation test, calibration value $\lambda$ is 0.90 to 0.95.
5.3. Effect of coarse aggregate shape

In order to reflect the effect of the shape of the aggregate, the spherical particles are used to simulate the impact of pebble aggregate, and the spherical particles are replaced by the same volume of tetrahedron and hexahedron to simulate gravel aggregate (figure 6). The comparison tests (4-1, 4-2 & 4-3) and (4-4, 4-5 & 4-6) show that the SCC is better passing ability to use the pebble aggregate than the gravel aggregate, then the shape of aggregate also influences the probability of passing and blocking of SCC (table 5). The different shapes of the gravel aggregate have different passing ability, and passing ability of the hexahedral particles are more than tetrahedral particles. The reason is to generate particles when a relatively large gap between spherical particles with mortar particles, the gap is mostly filled with mortar particles after replacement of polyhedron particles, then the contact of polyhedron particles in the process of movement is more closely with the mortar particles than the spherical particles, that leads to increased flow. But the tetrahedron particle simulation results are closer to the actual situation, it is better able to simulate gravel aggregate.

![Figure 6](image)

**Figure 6.** Different shape of coarse aggregate of (a) pebble; (b) gravel (1); (c) gravel (2).

| Test number | SCC number | Steel spacing(mm) | Aggregate size(mm) | Steel arrangement | Shape aggregate | Passing ability test/simulation (%) |
|-------------|------------|--------------------|-------------------|------------------|----------------|------------------------------------|
| 4-1         | No. 3      | 25                 | 5-10              | parallel         | Gravel (1)     | 36.1/42.9                          |
| 4-2         | No. 3      | 25                 | 5-10              | parallel         | Gravel (2)     | 36.1/46.3                          |
| 4-3         | No. 4      | 25                 | 5-10              | parallel         | Pebble         | 49.4/57.6                          |
| 4-4         | No. 3      | 20                 | 5-10              | parallel         | Gravel (1)     | 13.1/17.2                          |
| 4-5         | No. 3      | 20                 | 5-10              | parallel         | Gravel (2)     | 13.1/20.1                          |
| 4-6         | No. 4      | 20                 | 5-10              | parallel         | Pebble         | 15.9/22.3                          |

5.4. Effect of SCC flow

Three groups of flow contrast tests (5-1 & 5-2, 5-3 & 5-4, 5-5 & 5-6) show the flow of SCC can also affect the passing ability, the simulation results with the test results also reflect the same rule (table 6). It is pointed out that the probability of blocking is independent of rheological properties when it is...
stable, the blocking model Roussel proposed only for the case of particle blocking, and does not consider the effect of rheological properties. The decrease passing ability of SCC is completely the result of the decrease of its own flow, which has nothing to do with particle blocking probability. Therefore, the flow of SCC will also affect by test results, the effect is not achieved by changing the probability of particle blocking, but by changing the relationship between the yield stress and shear stress.

Table 6. Test results of changing SCC flow.

| Test number | SCC number | Steel spacing (mm) | Steel arrangement | Slump flow (mm) | Passing ability test/simulation (%) |
|-------------|------------|--------------------|------------------|----------------|-----------------------------------|
| 5-1         | No. 1      | 30                 | parallel         | 690×690        | 76.6/81.5                         |
| 5-2         | No. 2      | 30                 | parallel         | 550×550        | 36.9/32.4                         |
| 5-3         | No. 1      | 30                 | grid             | 690×690        | 43.3/38.4                         |
| 5-4         | No. 2      | 30                 | grid             | 550×550        | 22.4/19.3                         |
| 5-5         | No. 1      | 35                 | grid             | 690×690        | 72.4/64.7                         |
| 5-6         | No. 2      | 35                 | grid             | 550×550        | 100/83.6                          |

5.5. Effect of casting rate

The casting speed of concrete cannot be directly set in the discrete element, it can be simulated by giving the wall a certain speed [17]. The real physical time $T$ of Simulation test is calculated by $	ext{timestep} \times \text{step}$, after running a certain number of steps ($\text{timestep}=1.6 \times 10^{-4} \text{s}$), the volume of concrete particles is calculated and it is equal to that volume of different casting rate.

Table 7. Test results of changing casting rate.

| Test number | SCC number | Steel spacing (mm) | Steel arrangement | Casting rate (L/min) | Passing ability test/simulation (%) |
|-------------|------------|--------------------|------------------|----------------------|-----------------------------------|
| 6-1         | No. 1      | 30                 | parallel         | 1.5                  | 76.6/81.5                         |
| 6-2         | No. 1      | 30                 | parallel         | 3.0                  | 66.0/58.7                         |
| 6-3         | No. 1      | 35                 | grid             | 1.5                  | 36.9/32.4                         |
| 6-4         | No. 1      | 35                 | grid             | 4                    | 22.4/19.3                         |

Table 7 shows the influence of casting rate on passing ability of SCC, Compared with test 6-1 and 6-2, it can be seen that when the casting rate is 1.5 L/min, the passing ability of SCC is higher than the casting rate of 3.0 L/min. Compared with test 6-3 and 6-4, SCC can smoothly pass through the 35 mm grid steel when the casting rate is 1.5 L/min, when casting speed increased to 4 L/min, passing ability of SCC drops significantly. The increase of casting rate leads to the increase of flow rate, in fact, the rate of casting can influence the probability of particle blocking by changing the actual flow rate of SCC. According to the Bingham model, the plastic viscosity of SCC determines the speed of its flow, so the actual flow rate of SCC can also be affected by its plastic viscosity. Equation (7) does not take into account the flow rate of particles blocking probability, the influence of flow rate $\gamma$ shall be increased in the equation (7), the flow rate actually changes that local particle concentration of in front of the obstacles, so the parameter $\phi$ is changed to $\gamma\phi$, the particles blocking model formula is:

$$P = (2.6\Omega / D_{\text{max}}^3)(0.1\gamma\phi)^{0.85\beta^2/0.81(\beta D_{\text{max}})^2}$$

(9)

When flow rate is less than a certain critical value which the impact can be ignored, shows that the SCC has enough time to adjust its position when it meets obstacles, and will not lead to local aggregate content increased dramatically; when the flow rate is greater than this critical value, the change of casting rate will affect the passing ability of SCC. Therefore, parameter $\gamma$ has an upper limit, when the flow rate is greater than a certain critical value, even if the casting rate continues to increase, the local particle content of in front of the obstacle will not change, and the probability of
particle blocking will also not change. The flow rate is determined by the casting rate and the plastic viscosity, and it is controlled by changing the casting rate when the plastic viscosity is constant. The lower limit of the casting speed of Xie [4] is 1.5 L/min, and the maximum casting rate is capped at 7.8 L/min by using the conversion of physical time in the previous simulation test.

6. Summary
(1) The way of steel arrangement will have an effect on the passing ability and particle blocking probability of the SCC, steel arrangement (channel section shape) correction coefficient $\lambda$ was introduced into parameter $P$ and the value $\lambda$ of the simulated test was 0.90-0.95.

(2) The passing ability of pebble aggregate was superior to the gravel aggregate, passing ability of hexahedron particle was bigger than tetrahedron particle, but the tetrahedron particle simulation results were closer to the actual situation.

(3) The flow of SCC can also affect the passing ability, the effect was not achieved by changing the probability of particle blocking, but by changing the relationship between the yield stress and shear stress.

(4) The moving wall was used to simulate the casting speed of concrete, the flow rate parameter $\gamma$ was introduced and the maximum casting rate was capped at 7.8 L/min by using the conversion of physical time in the previous simulation test when the plastic viscosity was constant.

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