Numerical Simulation of Working Characteristics of Concrete Screw Conveyor Based on DEM

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Numerical simulation of concrete discharge of screw conveyor based on DEM

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Abstract. Screw conveyor is a kind of efficient and quantify discharging equipment according to the workability of materials. Based on the discrete element method (DEM), this paper establishes a screw conveyor simulation model to predict the discharging mode of concrete in the hopper and the movement of particles under the action of horizontal and combined-screws.The results show that the trapezoidal geometry structure of the hopper affects the hopper drawdown, and the particles squeeze and jam during the deposition movement, which is easy to cause the particles to agglomerate and form a "rathole formation". The movement of the particles to the screw filling area needs to be preferentially moved to the bottom of the screw to output horizontally under the shear action of the screw blade. At the same time, the cohesion of concrete particles has a great influence on the mass flow of screw continuous discharge. This provides an analytical method and theoretical basis for optimizing the geometry of the screw conveyor, improving the uniformity of the screw discharge, and reducing energy consumption.

1. Introduction

In the process of construction industrialization, the screw conveyor is one of the key equipment for concrete pouring production in the concrete forming process, and its performance directly affects the product quality and production efficiency of precast concrete components [1]. In the production of screw conveyors, there are problems such as inaccurate output, poor material uniformity, high energy consumption, large equipment wear, and variable material residence time.In actual use, it is necessary to improve the key structural parameters and process parameters of the equipment according to the physical properties of the materials, which results in high cost of product optimization design and long development cycle. With the development of computer technology, a method for visualization of bulk materials modeling, analysis of particle motion behavior, and interaction between particles and equipment geometry, the discrete element method, has been widely adopted by relevant scholars[2-3].Based on discrete element method numerical simulation of screw conveyor when the screw speed, screw inclination angle, material filling factor and other process factors change, the impact on screw output, key component wear, working efficiency and other performance[4-6] . While summarizing the changes in the technological factors of the screw conveyor, continue to analyze the impact of structural parameters such as screw parameters, screw length, and hopper shape on quantitative discharge, uniform discharge, energy consumption and other performance. In addition, the relationship between the micro flow characteristics of materials and the macro performance of screw conveying was explored[7-8].

While analyzing the process and structural parameters of the screw conveyor, understanding the flow characteristics of the materials is critical to optimizing the structural design and parameters.Fresh concrete is difficult to accurately predict the workability and rheology due to the complex raw material ratio and changes in environmental conditions. Relevant scholars usually conduct a lot of research in experimental testing, numerical simulation, and theoretical analysis. In order to analyze the workability of concrete, a lot of research is used to establish the theoretical model of concrete[9-10]. In the establishment of a theoretical model of fresh concrete, concrete can be regarded as a single-phase fluid based on hydrodynamic theory, such as the Bingham model. In engineering, the change of flow and pressure in concrete flow can be analyzed, such as pumping concrete[11]. However, this model cannot reflect the heterogeneity of the concrete mixture in the flow process, such as the deposition effect of concrete materials in the hopper, the segregation of concrete, the filling of materials in the screw gap and other complex behaviors. Another concrete modeling method, discrete element method (DEM), considers concrete as an aggregate of particles, and the motion behavior between particles is controlled by the force-displacement constitutive equation between particles[12].In the DEM modeling of concrete, the coarse aggregate of gravel in concrete is mainly built into discrete unit according to the change of particle size, while the fine aggregate of mortar can be built into different models according to the research problems. The single particle model mainly describes the coarse aggregate of gravel, and the mortar filled between the aggregates is defined by the constitutive relationship between the particle models. The two unit models mainly describe coarse aggregates of gravel and fine aggregate particles of mortar[13]. For example, self-compacting concrete is described as a sticky bridge model with cohesive between particles, used to analyze the flow characteristics of mortar and aggregates, and the uniformity of mixing. In this paper, the influence of material flow on structural and technological parameters is analyzed on the micro scale. The discrete element method has more advantages than the flow dynamics method.

In this paper, based on the discrete element method, the concrete material is described as consisting of two-phase single particles of mortar and coarse aggregate of gravel. The interaction between mortar and coarse aggregate is controlled by proper constitutive relationship. The DEM model parameters of concrete are calibrated by standard flow experiment. The numerical simulation of concrete particles in the screw conveyor is carried out in the drawdown, the filling rule of particles and the problems that are easy to occur in the discharging. It provides the analysis method and theoretical basis for optimizing the equipment structure parameters, process parameters and realizing the uniform discharging.

2. Materials and Methods

In this study, aggregates of gravel and mortar were considered as solid phases in the DEM numerical simulation. gravel aggregates are non-cohesive particles, and mortar aggregates are cohesive particles. In DEM simulation, there are translation and rotation motions of particles and particles or geometric walls under interaction, which is calculated by Newton's second law of motion. Within the calculation period t, the equation of motion of the particle i with the control mass and radius Ri can be written as:

$$m_{\mathrm{i}} \frac{dv_i}{\mathrm{dt}} = \sum_{\mathrm{j=1}}^{\mathrm{k_i}} \left(f_{e,ij} + f_{d,ij} + f_{coh,ij} \right) + m_i g \qquad （1）$$

$$I_{\mathrm{i}} \frac{d\omega_i}{\mathrm{dt}} = \sum_{\mathrm{j=1}}^{\mathrm{k_i}} \left(T_{ij} + M_{ij} \right) \qquad （2）$$

Where m_i , I_i , V_i and ω_i are the mass,moment of inertia,translational velocity,and rotational velocity of particle i,respectively,g is the acceleration due to gravity,j represents a particle i, F_{e} represents the elastic force,which is the summation of the normal and tangential forces $F_{\mathrm{cn,ij}}$ and $F_{\mathrm{ct,ij}}$,respectively,at the contact point with particle j, F_{d} represents the damping force,which is the summation of the normal and tangential damping forces, $F_{\mathrm{dn,ij}}$ and $F_{\mathrm{dt,ij}}$,at the contact point, $F_{\mathrm{coh,ij}}$ is the cohesive force between particle i and j which are not necessarily in contact,and T_{ij} and M_{ij} are the torque due to the tangential components of the contact forces and rolling friction torque on particle i form particle j,respectively.The equations for the contact forces and torques in Eqs.1 and Eqs.2 are given elsewhere[14].

In the DEM numerical simulation, the gravel particles used Hertz-Mindlin no- slip model [15].The mortar aggregate is based on the Hertz-Mindlin no-slip model, using the Johnson-Kendall-Roberts theory[16],considering the contact radius a between particle overlaps and the particle cohesion coefficient γ,calculating the normal elastic contact of the particles force.The geometric model of the screw conveyor is shown in Figure 1.

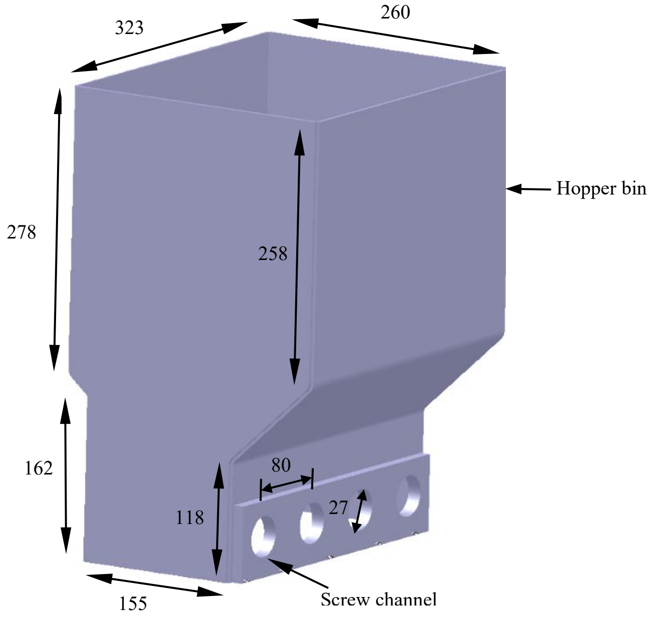

Figure 1. Hopper bin, screw channel geometry with dimensions shown(mm).

The accuracy of the numerical simulation prediction results of concrete screw conveyance depends on the model parameters checked. In order to accurately describe the macroscopic flow state of concrete, the DEM model parameters of gravel and mortar were obtained by direct and indirect measurement. The measurement method of physical parameters of gravel and mortar materials [17-20] is shown in Figure 2. A vibrating sieve is used to measure the range of particle size of gravel. The density of particles was measured using a pycnometer. Through the drop test, the restitution coefficient of gravel, mortar ball, and contact wall was measured by a high-speed camera. Through the sliding experiment device, the static friction coefficient and the rolling friction coefficient between the gravel, the mortar ball and the steel plate are measured by the high-speed camera.The cohesion coefficient of mortar was measured by V-funnel experiment and numerical simulation. By comparing the numerical simulation results and the experimental results of the concrete standard experiment, based on the experimental results, the rolling friction coefficient and the cohesion coefficient of the particles in the simulation are revised, so that the numerical simulation results are infinitely approach to the experimental measured values.

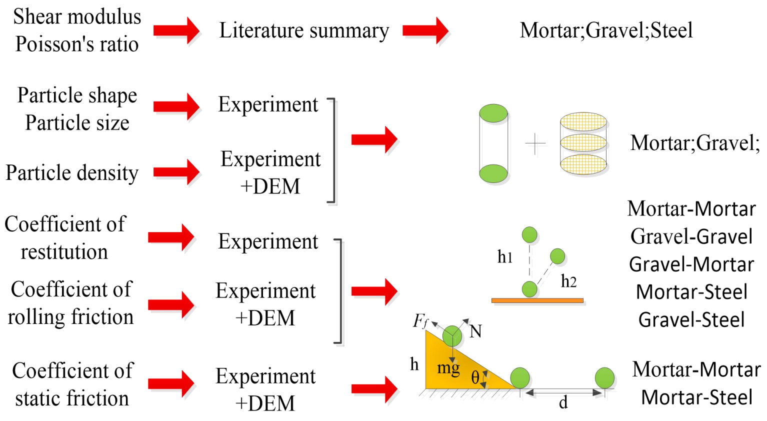

Figure 2. Measurement methods of physical parameters of gravel and mortar materials

Figure 3 shows the numerical simulation and test results of the concrete standard test.It can be seen from the figure that the numerical simulation of concrete V-funnel has good consistency with the measured emptying time under the experiment. The model parameters of concrete can be used to analyze the hopper drawdown and particle transportation of the screw conveyor. Numerical simulation analysis shows that the friction coefficient and cohesion coefficient have significant effects on the particle-particle and particle-contact wall interactions. The parameters of the concrete discrete element model are shown in Table 4.

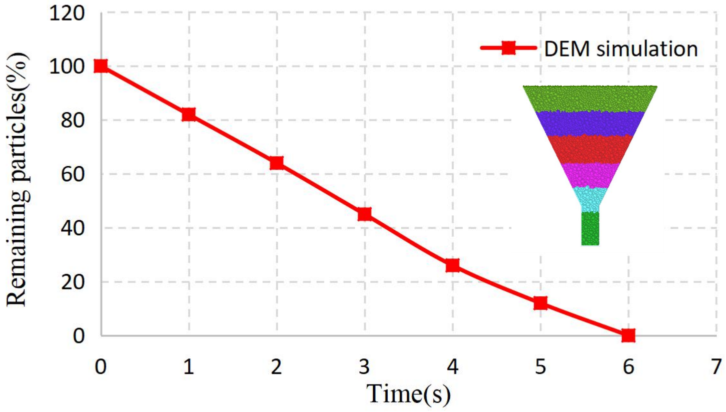

Figure 3. Concrete V-funnel simulation and experimental results

Table 4 Concrete material particle properties

Parameter	Gravel-gravel	Gravel-mortar	Mortar-mortar	Mortar-steel	Gravel-steel
Poisson's ratio	0.35	-	0.4	0.3	-
Particle density	2591	-	3210	7850	-
Shear modulus	2e+10	-	2e+10	7.8e+10	-
Particle size	10	-	5	-	-
Cohesion coefficient	-	-	3.8	2.5	-
Coefficient of restitution	0.05	0.04	0.01	0.01	0.1
Coefficient of static friction	0.47	0.52	0.25	0.18	0.43
Coefficient of rolling friction	0.1	0.13	0.08	0.06	0.08

3. Results discussion

3.1 Hopper drawdown of screw conveyor

In the numerical simulation, concrete particles fall into the hopper under the action of gravity and cohesion and are randomly piled up in the screw fill area.This filling mode can represent the process of screw conveyor filling concrete in production.The initial filling material in the hopper is 40% of the volume of the hopper. According to the calculation of the concrete proportioning, 8110 gravel particles and 59260 mortar particles are obtained. The hopper geometry can be divided into two parts, the upper part is a rectangular domain and the lower part is a trapezoidal domain. In order to clearly describe the drawdown of the concrete particles in the hopper, analyze the movement behavior of the particles in the screw gap, and set the concrete particles in the hopper along the vertical screw conveying direction (x-axis) with four color accumulation areas, as shown in Figure 4(t=7s). The color of the materials is set in blue, yellow, green, and red in order from the back to the front of the hopper. Among them, yellow and green particles are accumulated in the middle area of the hopper, and the remaining two color particles are accumulated in the areas on both sides of the hopper.When the concrete particles in the hopper are stable, the screw rotates and pours in a left-hand and right-hand staggered way, and the drawdown of the particles in the hopper is shown in Figure 4.

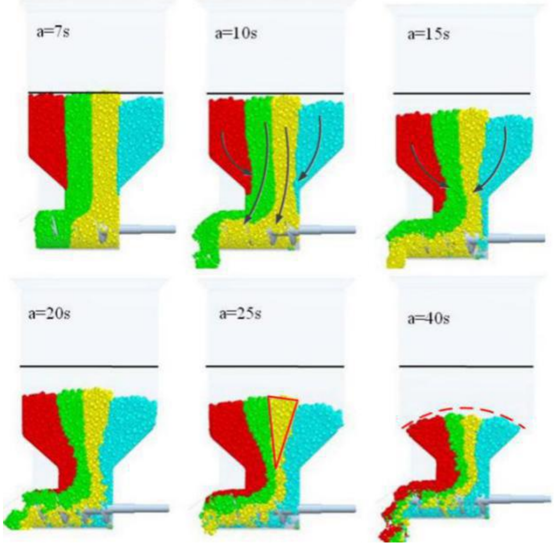

Figure 4. Concrete particle drawdown in the hopper of the screw conveyor

When the particles in the hopper are in a quasi-equilibrium state, the discharge gate is opened, and the screw speed outputs the particles at a level of 30r/min.When the discharge time is 7s, the yellow and green particles in the screw gap move along the axial direction of the screw under the shear action of the screw blade. when the discharge time is 10s, the initially filled green particles in the screw gap are completely discharged. The screw root gap is completely filled with yellow particles. The red and blue particles in the hopper penetrate into the gaps that appear during the downward deposition of yellow and green particles. It can be seen that the flow direction of the particles in the hopper is as indicated by the arrow. The downward deposition of particles shows a significant "squeeze" phenomenon at the exit of the trapezoidal domain. The green and yellow particle bands have a twisted shape with a wide upper part and a lower narrow part. As the discharge time increases, the blue and red particles move further toward the middle area along the arrow indication, and some particles have been filled into the screw gap. When the discharge time is 25s, the accumulation shape of the green and yellow particles becomes an inverted triangle, and the particles in the hopper have an "arch bridge" phenomenon.

The particles in the hopper can only be filled into the entire gap and smoothly discharged under the shearing effect of the screw blades only when they are filled into the gap of the screw root.The green particles cannot enter the screw gap due to position limitation, and can only be output horizontally along the outer diameter of the screw under the interaction of particles in the screw gap. As the yellow particles are discharged in large quantities, the resulting gap is filled with blue particles and smoothly moves to the bottom of the screw. When the discharge time reaches 40s, the screw gap is filled with a large number of blue particles, and the yellow particles remain less and less, and can no longer move to the bottom of the screw. A large number of red particles continue to move along the upper edge of the outer diameter of the screw instead of the green particles. At this time, four kinds of color particles can be observed to flow out at the discharge port.

3.2 Mass flow of particles

In the numerical simulation of screw conveying concrete, the mass flow of different color particles collected in 1s time step is shown in Figure 5.

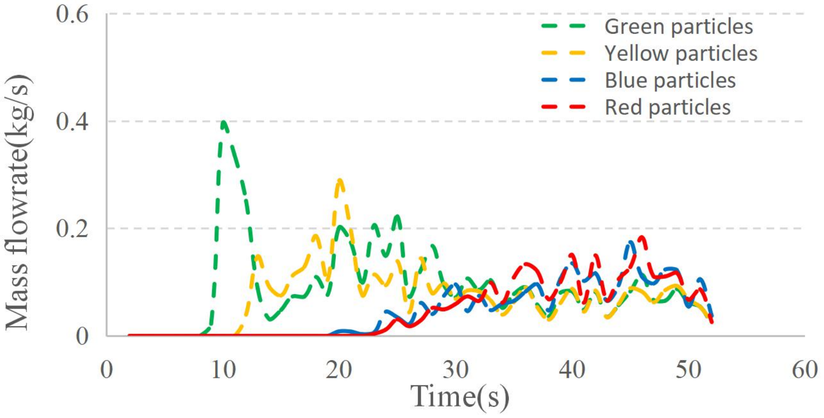

Figure 5. The mass flow rate of particles with different colors

As shown in Figure 5, the screw output in the first 25s is mainly yellow and green particles and the mass flow fluctuation is large. After 25s, the mass flow of yellow and green particles tended to stabilize, and the mass flow of blue and red particles increased and the fluctuation range increased. It can be seen from Figure 4 and Figure 5 that the particles in the middle area of the hopper are preferentially filled into the screw gap, and the position of particle filling affects the order of particle output.The concrete particles are filled into the screw gap in clusters. The compaction rate of the particles in the continuous discharge is affected by the height of the particles in the hopper, causing the gap between the particles to change. Therefore, the particles appear intermittent and stable in continuous flow.

4. Conclusion

In this paper, based on the discrete element method (DEM), the numerical model of the concrete screw conveyor is established, and the drawdown mode and movement direction of different color particle along the vertical screw discharge direction are qualitatively analyzed. Significantly, the particles are deposited under the action of cohesion and gravity, and priority filling occurs in different colour regions. The movement direction of the particles is to fill the gap of the screw root preferentially, and then move from the root of the screw to the front of the screw under the shearing action of the blade. The cohesiveness of concrete particles has a great influence on the discharge mode and screw conveyance.

Acknowledgments

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References

[1] D.F.Zou,Technique and outfit of large-scale intelligent PC external wall panel mixing production line. IOP Conf. Series: Materials Science and Engineering.2018(399)12-18.

[2] P.A.Cundall,O.D.L.Strack,A discrete numerical model for granular assemblies,Geotechnique 29 (1979)47–65.

[3] J.W.Fernandez,P.W.Cleary,W.McBride, Effect of screw design on hopper draw-down of spherical particles in a horizontal screw feeder, Chemical Engineering Science.66 (2011)5585–5601.

[4] Q.F.Hou,K.J.Dong,A.B.Yu,DEM study of the flow of cohesive particles in a screw feeder,Power Technology.256(2014)529-539.

[5] L.Orefice,J.G.Khinast,DEM study of granular transport in partially filled horizontal screw conveyors, Powder Technology.2017(305), 347–356.

[6] Pezo.M,Pezo.L,Jovanović.A,et al.Discrete element model of particle transport and premixing action in modified screw conveyors.Powder Technology.2018(336), 255-264.

[7] Mohammad M,Tekeste M Z,Rosentrater K A.Calibration and Validation of a Discrete Element Model of Corn Using Grain Flow Simulation in a Commercial Screw Grain Auger[J].Transactions of the ASABE,2017,60(4):1403-1415.

[8] L.Pezoa,A.Jovanovica,M.Pezob,et al.Modified screw conveyor mixers—discrete element modeling approach,Adv.Powder Technology.26(2015)1391-1399.

[9] Mechtcherine V,Gram A,Krenzer K,et al.Simulation of fresh concrete flow using Discrete Element Method (DEM): theory and applications[J].Materials and Structures, 2014,47(4):615-630.

[10] Remond S,Pizette P.A DEM hard-core soft-shell model for the simulation of concrete flow[J]. Cement and Concrete Research, 2014, 58:169-178.

[11] Yijian,Zhan,Jian,et al.Numerical Study on Concrete Pumping Behavior via Local Flow Simulation with Discrete Element Method.[J].Materials (Basel, Switzerland), 2019.

[12] Mechtcherine V,Gram A, Krenzer K,et al.Simulation of fresh concrete flow using Discrete Element Method (DEM). In:Roussel N, Gram A,editors.Simulation of fresh concrete flow. RILEM State-ofthe-Art Reports;2014.p.65–98.Vol.15.

[13] Qian Z,Garboczi E J,Ye G,et al.Anm: a geometrical model for the composite structure of mortar and concrete using real-shape particles[J].Materials and Structures, 2016,49(1-2):149-158.

[14] Chandratilleke R,Yu A,Bridgwater J,et al.Flow and Mixing of Cohesive Particles in a Vertical Bladed Mixer[J].Industrial & Engineering Chemistry Research,2014, 53(10):4119-4130.

[15] Yang M,Li S,Yao Q.Mechanistic studies of initial deposition of fine adhesive particles on a fiber using discrete-element methods[J].Powder Technology,2013, 248:44-53.

[16] Johnson K L,Kendall K,Roberts A D.Surface Energy and Contact of Elastic Solids[J].Proceedings of The Royal Society A,1971,324(1558):301-313.

[17] Bouziani T,Benmounah A.Correlation between v-funnel and mini-slump test results with viscosity[J]. KSCE Journal of Civil Engineering, 2013, 17(1):173-178.

[18] Stahl M, Konietzky H.Discrete element simulation of ballast and gravel under special consideration of grain-shape,grain-size and relative density[J].Granular Matter, 2011, 13(4):417-428.

[19] Chen Z,Yu J,Xue D,et al.An approach to and validation of maize-seed-assembly modelling based on the discrete element method[J].Powder Technology.

[20] C.González-Montellano, á. Ramírez,Gallego E, et al.Validation and experimental calibration of 3D discrete element models for the simulation of the discharge flow in silos[J]. Chemical Engineering Science, 2011, 66(21):5116-5126.