Research Article

Migration Characteristics and Restoration Mechanism of Grout Containing Aggregate in Overburden Fractures Based on CFD-DEM Coupling Model

Yulou Ren,1 Feng Du,2,3 Huanqi Chen,1 Zijie Hong,1 and Ziyuan Ren2

1School of Civil Engineering, Henan Polytechnic University, Jiaozuo, 454000 Henan, China
2School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, 454000 Henan, China
3Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Jiaozuo, 454000 Henan, China

Correspondence should be addressed to Feng Du; fdu_cumt@126.com

Received 6 May 2022; Accepted 27 June 2022; Published 14 July 2022

Academic Editor: Liang Xin

Copyright © 2022 Yulou Ren et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In order to improve and restore the strength and stability of broken overburden caused by coal seam mining in underground, the grout containing aggregate is employed to backfill specific fracture space in rock strata, which is an important method to prevent the mine water leakage and roof collapse in working face. Therefore, the migration characteristics and restoration mechanism of grout containing aggregate in overburden fractures based on the CFD-DEM coupling model are researched in this paper. Specifically, the mechanical constitutive model of aggregate migration is obtained by mechanical analysis of particles and flow field, and the mechanism of aggregate flow and transport with grout in rock fracture is put forward. Besides, the coupled CFD-DEM model is built by numerical simulation software, and the transport process of grout containing aggregate in the fracture is numerically calculated. On this basis, the transport law and deposition characteristics of aggregate transport with grout are studied, and the inner mechanism of the change law is obtained. The research results indicate that the aggregate is gradually deposited by various “settlement forces” during the migration process. The smaller the particle size and density of aggregate are, the slower the deposition rate of aggregate particles and the longer the migration distance are. The aggregate with particle size of 3 mm and density of 3250 migrates 1.25 m to reach the maximum solid ratio of 12.9%. The settlement ratio reaches 100% after migration of 1.5 m, and the longest migration distance is 1450 mm. In addition, the solid ratio of each aggregate firstly increases and then decreases with its migration, which is analyzed from the perspective of aggregate deposition and concentration change. When the aggregate density of two particle sizes changes from 3500 to 3750, the aggregate migration distance is significantly reduced. The research results provide an important guiding significance for reasonably selecting aggregate parameters and optimizing the design of grouting holes in mining engineering.

1. Introduction

Under the multiple influence of geological movement and mining stress, rock strata are broken to produce various kinds of pores and fracture in underground [1]. As a result, the permeability and bearing capacity of rock mass change, which leads to the drainage of mine roof water, causing the occurrence of water inrush accident [2]. Adding aggregate into the grout for grouting filling of specific fracture space manually repairs large-scale fractures, so as to strengthen the rock stratum, and blocks the water diversion fracture zone and reduces the occurrence of water inrush accidents [3]. The migration and diffusion of aggregate in rock fracture with grout is the key and difficult point in grouting technology. Factors such as material properties and size of aggregate have an important impact on its migration characteristics with grout [4]. The selection of appropriate parameters is beneficial for the better migration and diffusion of aggregate in rock fracture with grout.

Scholars had done many research on the migration and diffusion mechanism of grout in fractures. In terms of theoretical research, Yang et al. [5] deduced the calculation
formula and solution method of diffusion radius of Bingham grout in the process of infiltration grouting. Wang et al. [6] proposed a grout diffusion model and a calculation method for fracture grouting considering the effect of grout dewatering. In terms of experimental research, Dong et al. [7] designed a visual three-dimensional simulation test system, discussed several influencing factors in the grouting process, and quantitatively analyzed the influence of various factors on the grouting effect. Pang and Yao [8] analyzed the effects of formation water content, water cement ratio and grouting pressure on grout diffusion radius, grouting volume, and strength growth rate through the self-developed indoor grouting test device. Wang et al. [9] studied the diffusion law of aggregate with grout in rock mass fractures, especially there is no relevant numerical calculation model of solid-liquid two-phase flow.

et al. [6] proposed a grout diffusion model and a calculation method for fracture grouting considering the effect of grout dewatering. In terms of experimental research, Dong et al. [7] designed a visual three-dimensional simulation test system, discussed several influencing factors in the grouting process, and quantitatively analyzed the influence of various factors on the grouting effect. Pang and Yao [8] analyzed the effects of formation water content, water cement ratio and grouting pressure on grout diffusion radius, grouting volume, and strength growth rate through the self-developed indoor grouting test device. Wang et al. [9] studied the diffusion law of aggregate with grout in rock mass fractures, especially there is no relevant numerical calculation model of solid-liquid two-phase flow.

To solve the above problems, the coupling model of large particle size solid particles and Bingham fluid, namely, CFD-DEM coupling model, is established in this paper. CFD module is mainly employed to simulate the grout with selected viscosity, and the FLUENT numerical software is chosen. The particle system is mainly used to simulate the aggregate carried in the grout, and the proposed EDEM numerical software is chosen. The solid-liquid two-phase flow is coupled through the Euler interface, and the mass, momentum, and energy are transmitted through the interface, so as to realize the coupling simulation calculation of particles and fluid. Based on the above CFD-DEM coupling model, the diffusion and flow characteristics of aggregate and grout in the no pressure or low pressure stage of rock fracture are studied from the micropoint of view. Taking the ratio of the volume of settled particles to the total volume (solid volume ratio) and the ratio of the mass of settled particles to the total particle mass (settlement mass ratio) as the monitoring objects, the effects of aggregate particle size and density on the deposition characteristics of aggregate in the process of flowing with grout are studied, and the deposition law of bone is explained from the microscopic point of view.

2. Flow Field Theory

2.1. Motion Theory of Aggregate Particles in Flow Field. The fluid forces acting on the aggregate particles in the grout mainly include drag force, pressure gradient force, rotational force, and Saffman lift [14], and Saffman lift [15]. The calculation formulas of drag force, pressure gradient force, rotating lift, and Saffman lift are obtained.

\[ F_d = \frac{1}{2} C_d \rho A_p |v| |v_s| \]  \hspace{1cm} (1)

\[ F_p = -\nabla p_{\text{static}} \]  \hspace{1cm} (2)

\[ F_{\text{LR}} = \frac{\pi \rho}{8} D_p^2 C_{\text{LR}} |v| \frac{\Omega v_s}{|\Omega|} \]  \hspace{1cm} (3)

\[ F_s = 1.615 (\mu)^{1/2} D_p^2 |v_s| \left| \frac{dv_f}{dy} \right|^2 \text{sign} \frac{dv_f}{dy}. \] \hspace{1cm} (4)

\( F_d, F_p, F_{\text{LR}}, \) and \( F_s \) are drag force, pressure gradient force, rotational lift force, and Saffman lift force, respectively; \( v_s \) is the particle slip velocity, that is, the instantaneous velocity difference between fluid and particle; \( C_j \) is the drag coefficient; \( \rho \) is the fluid density; \( A_p \) is the particle projection area; \( V_p \) is the particle volume; \( \nabla p_{\text{static}} \) is the hydrostatic gradient; \( D_p \) is the particle diameter; \( C_{\text{LR}} \) is the rotational lift coefficient; \( \Omega \) is the particle slip angular velocity; \( \mu \) is the fluid viscosity; and \( v_s \) is the fluid viscosity. The directions of drag force, pressure gradient force, rotational lift force, and Saffman lift force are related to the motion state of aggregate particles, and their main directions are shown in Figure 1.

The Saffman lift is special, which mainly occurs near the velocity boundary layer (fracture wall), which is ignored in the velocity mainstream area (with small velocity gradient), and the direction of Saffman lift is related to the particle slip velocity. When the slip velocity is positive, the main direction of Saffman lift is upward; otherwise, it is downward. When the aggregate particles flow with the grout, they are mainly affected by the “propulsive force” and “settling force,” in which the drag force is the main driving force for the particles to move forward with the grout, that is, the so-called “propulsive force.” The resultant force of pressure gradient force, rotational lift, Saffman lift, and gravity are the main parts of the “settling force” received by the particles.

2.2. Velocity Stratification Mechanism of Viscous Fluid. The calculation formula of Newtonian internal friction force is

\[ F = \mu A \frac{dv}{dy}. \] \hspace{1cm} (5)

The fluid studied in this paper belongs to Bingham fluid, which is a typical viscous fluid [16, 17]. According to Newton’s law of internal friction, there is internal friction between different flow layers in the fluid domain, which affects the flow velocity of each flow layer [18]. There is adhesion between the fluid flowing in the fracture and the wall; so, the velocity of the thin layer of fluid adhering to the fracture wall is 0. In addition, the fluid flow in the
adjacent layer is obstructed by internal friction, then the fluid velocity in the adjacent layer is reduced, and finally, the velocity in the fluid domain near the fracture wall is significantly reduced. The fluid stratified flow diagram and cloud chart of fluid velocity in single fracture flow field are shown in Figures 2 and 3, respectively.

The fluid in region I and region III becomes a low-speed zone due to its proximity to the wall, while the fluid in region II is a high-speed zone. Finally, a bullet-like fluid domain is formed at the front end of the fluid. At the same time, this phenomenon causes the velocity of aggregate in the fluid in the central area to be greater than that in other areas, which further reduces the aggregate concentration in the process of migration.

3. Numerical Simulation of Fluid-Solid Coupling Fields in Grout Containing Aggregate

3.1. Basic Parameters of CFD-DEM Coupling Fields. The schematic diagram of grout flowing in fracture is shown in Figure 4, on the one hand, it diffuses along the horizontal direction; on the other hand, the solid phase material in the grout is deposited under the action of gravity [6, 19]. This paper mainly studies the deposition characteristics of the aggregate when it flows with the grout.

Fracture size is as follows: length \( l = 2000 \) mm, fracture width \( B = 8 \) mm, and fracture height \( H = 50 \) mm; the fracture is set as horizontal fracture; the constant velocity inlet is selected for the fracture inlet, and the velocity is set to 0.8 m/s; the liquid phase studied in this paper is the mixture of water, cement, fly ash, and other materials. Due to the large difference between the particle size of cement, fly ash, and aggregate, its discreteness is ignored, and it (grout composed of cement, fly ash and other particles uniformly mixed with water) is unified as the liquid phase. As a typical Bingham fluid, the grout is simulated by Herschel-Bulkley model.

The constitutive equation of the Herschel-Bulkley model is obtained in equation (6).

\[
\tau = \tau_0 + K\gamma^n.
\]  

\( \tau \) is the shear stress, \( \tau_0 \) is the yield stress, \( K \) is the consistency, \( \gamma \) is the shear rate, and \( n \) is the liquidity index.

The solid particles are set as single spherical particles, and the Hertz-Mindlin soft ball model is adopted. The shear modulus is 0.47 GPa, Poisson’s ratio is set as 0.3, and the number of particles is set as 2000 per second. In order to simulate the on-site aggregate more truly, a random range of 0.9 ~ 1.1 is applied to the particle size; that is, the aggregate is in \( D \times 0.9 ~ D \times 1.1 \) randomly generated within the range of 1.1 \( (D \) is the particle size of aggregate, mm). Aggregate density and particle size are shown in Table 1.

3.2. Simulation of Aggregate Particle Migration. The cloud map of the migration speed of aggregate particles of each density with the grout in the fracture under the particle size of 3 mm and 4 mm is shown in Figure 5, and the cloud map of the volume fraction of aggregate particles of each density under the particle size of 3 mm and 4 mm is shown in Figure 6.

(1) Aggregate particles gradually deposit with the flow of grout. The deposition trend of aggregate particles with two particle sizes is basically the same. The flow distance of aggregate particles with the same particle size with the grout decreases with the increase of aggregate particle density. The migration distance of aggregate particles with particle size of 3 mm and density of 3250 is the longest, reaching 2873 mm. The transport distance of aggregate particles with particle size of 4 mm and density of 4000 is the shortest, which is only 1450 mm. Moreover, for two kinds of aggregate particles, when the density changes from 3250 to 3500 and from 3750 to 4000,
the reduction of aggregate migration distance is small; while when the density of aggregate particles changes from 3500 to 3750, the aggregate migration distance decreases significantly.

(2) When aggregate particles are basically deposited, the flow distance of aggregate particles with a diameter of 3 mm is larger than that of aggregate particles with a diameter of 4 mm on the whole. In the experimental group with 3 mm particle size, the shortest migration distance is the aggregate particles with 4000 density, and the migration distance is 1994 mm, while in the experimental group with 4 mm particle size, the longest migration distance is only 1904 mm, corresponding to the aggregate particles with 3250 density. The larger the particle size of aggregate, the faster the deposition speed; so, the shorter the flow distance. In each group of experiments in this paper, the particle size has a greater impact on its deposition speed and migration distance. The velocity cloud of grout with 3 mm and 4 mm particle sizes of aggregates of various densities in a single fracture is shown in Figure 7.

The maximum flow velocity of grout carrying 3 mm and 4 mm aggregate is close to 1 m/s, while the flow velocity set at the fracture inlet is only 0.8 m/s, which is inconsistent with the cloud map of fluid flow velocity. It is considered that with the flow of grout, the aggregate gradually deposits, and this aggregate accumulation phenomenon gradually reduces the flow section of grout in the fracture. When the
inlet flow is constant, the grout velocity increases due to the reduction of the flow section at the aggregate accumulation. The maximum velocity in the fluid velocity cloud map is located at the position with large accumulation of particle, while the grout velocity recovers to near 0.8 m/s at the position with small accumulation of particle. This phenomenon is consistent with the above analysis. The maximum velocity of the grout carrying 3 mm size aggregate is less than that of the grout carrying 4 mm size aggregate, and the flow distance corresponding to the maximum flow velocity of the former is greater than that of the latter. It is considered that the accumulation formed by aggregate deposition leads to the reduction of fracture flow section, and the minimum value of flow section caused by 4 mm particle size aggregate accumulation is greater than the minimum value of flow section caused by 3 mm particle size aggregate accumulation; so, the maximum value of grout flow velocity in the fracture corresponding to 3 mm particle size is greater. Compared with the aggregate particle accumulation with the particle size of 4 mm, the position of the aggregate accumulation with the particle size of 3 mm is slightly behind, making the position of the maximum value of grout velocity in the fracture with the particle size of 3 mm slightly behind.

4. Result Analysis of Numerical Simulation

By observing and analyzing the particle velocity cloud map in each scheme, it is obtained that when the particle settles to a certain height, it enters the slow speed zone, and its horizontal velocity decreases significantly, which is different from the particle velocity in the fracture center zone. Cloud map of local velocity of single fracture is shown in Figure 8, and the velocity cloud map at 3 mm particle size is taken as an example.

The particle velocity in the center of the fracture is large, while the velocity of the particle below the red line is obviously lower than that in other areas. By studying the variation rules of particles in the zone below the red line, the deposition rules of aggregate particles in the process of grout flow are obtained.

According to the above conclusions, this section intends to make statistics of the change of solid ratio and settlement ratio of aggregate particles in the process of grout flow. Solid ratio refers to the ratio of solid particle volume to total grout volume in the area below the red line, referred to as solid ratio; sedimentation ratio refers to the ratio of the mass of aggregate particles below the red line to the mass of aggregate particles within all heights (below and above the red line). Due to the same particle density, the mass ratio of the two is expressed by volume ratio. In order to avoid the influence of the irregular settlement of the aggregate particles on the statistics, this paper adopts the method of multipoint sampling and average value to reduce the accidental error, so as to ensure the accuracy of the data of solid ratio and settlement ratio. The measuring points are set at 0.05 m, 0.25 m, 0.5 m, 0.75 m, 1 m, 1.25 m, 1.5 m, 1.75 m, 2 m, 2.5 m, and 2.75 m, respectively. The first measuring point is set at 0.05 m to prevent data distortion caused by
unstable fluid flow near the grouting hole. At each measuring point, the statistical data of three different sampling points are set and averaged.

4.1. The Change Rule of Solid Ratio of Aggregate Particles of Different Densities under Two Sizes with the Grout Flow Process. The solid phase in this paper is aggregate particles. Particles such as fly ash and cement are treated as liquid phase due to their size difference from aggregate. The change of solid ratio can reflect the deposition law of aggregate with grout flow. The change rule of solid ratio of aggregate particles with different densities at 3 mm and 4 mm particle sizes in the process of grout flow is shown in Figure 9.

(1) In the process of grout flow, the change trend of solid ratio of each density of aggregate under the two particle sizes is basically the same, which increased firstly and then decreased. Aggregate is deposited gradually by gravity in the process of transportation, and aggregate deposition makes the solid ratio of statistics increase, but the deposition and flow stratification phenomenon makes the concentration of aggregate continue to decrease in the process of transportation, and the decrease of aggregate concentration leads to the decrease of aggregate deposition, which leads to the decrease of aggregate solid ratio; so, both deposition and aggregate concentration affect the solid ratio. In the first and middle period of aggregate transport, the deposition of aggregate is greater than the reduction of its concentration, and the deposition of aggregate is the main factor affecting the solid ratio; so, it is reflected that the solid ratio of grout increases with its flow distance; while in the middle and late period of aggregate migration, due to the obvious reduction of aggregate concentration, the concentration of aggregate becomes the main factor affecting the solid ratio, which is reflected that the solid ratio decreases with the reduction of aggregate concentration. In the first and middle period of aggregate transport, the deposition of aggregate is greater than the reduction of its concentration, and the deposition of aggregate is the main factor affecting the solid ratio; so, it is reflected that the solid ratio of grout increases with its flow distance; while in the middle and late period of aggregate migration, due to the obvious reduction of aggregate concentration, the concentration of aggregate becomes the main factor affecting the solid ratio, which is reflected that the solid ratio decreases with the reduction of aggregate concentration.

(2) For both 3 mm and 4 mm particle size aggregates with the grout flow process, the following conclusions are obtained. For 3 mm and 4 mm aggregates,
it is the aggregates with density of 4000 that reach the maximum value of solid comparison first, and the maximum value of solid comparison for 3 mm particle size appears at the measurement point of 0.75 m with a maximum value of 18.3%. The maximum value of the solid ratio of 4 mm particle size occurs at the 0.5 m measurement point, and the maximum value is 35.7%. For the same particle size of aggregate particles, increased density leads to an increase in its gravity; so, the aggregate by the “settlement force” is increased, and the deposition rate is faster, which also leads to the density of the aggregate to reach the maximum value of solid compared to the required horizontal flow distance is shorter.

4.2. The Variation Law of Settlement Ratio of Each Density of Aggregate Particles under Two Particle Sizes in the Process of Flowing with Grout. By studying the settlement ratio of the aggregate particles, the diffusion distance of the aggregate with the grout under various working conditions can be obtained, so that the diffusion radius of the aggregate and its influencing
factors are obtained. The variation of settlement ratio during transport of aggregate particles with different densities at 3 mm and 4 mm particle size is shown in Figure 10.

The trend of settlement ratio for each density of aggregates with grout flow is basically the same for both particle sizes, and the settlement ratio increases with the flow distance of aggregates and grout. At the same flow distance, the settlement ratio of aggregates of two particle sizes increases with the increase of aggregate particle density. In the test group with 3 mm particle size, aggregate particles with densities of 3750 and 4000 achieve 100% settlement ratio at the measurement point of 2 m firstly. In the 4 mm particle size test group, aggregates with densities of 3750 and 4000 achieve a 100% settlement ratio at the 1.5 m measurement point firstly. This further demonstrates that as the density of aggregate particles increases, the deposition rate is increasing, and the settling is more rapid. For the phenomenon that the aggregates with densities of 3750 and 4000 in the 3 mm and 4 mm particle size test groups reached 100% settlement ratio at the same measurement point, the measurement point is not set precisely at the point where the settlement ratio of the test group just reaches 100% and causes statistical errors and does not reach 100% at the same time.

4.3. The Variation Law of Solid Comparison of Two Particle Sizes of Aggregates with Grout Flow Distance at Different Densities. The variation of solid ratio of aggregate particles

Figure 9: Change curves of solid ratio of aggregates with different particle sizes as a function of flow distance.

Figure 10: Variation of settlement ratio of aggregates with their flow distance at different particle sizes.
of different particle sizes with grout flow at different densities is shown in Figure 11.

(1) In the process of flowing with grout for 4 densities of aggregates, the solid ratio of 3 mm particle size and 4 mm particle size of aggregates both increases firstly and then decreases. The rate of increase and decrease of solid ratio of 4 mm aggregate is fast, compared to the slow increase and decrease of solid ratio of 3 mm aggregate. The solid ratio of 4 mm particle size is greater than the maximum value of solid ratio of 3 mm particle size at the same density, and the difference between the maximum values of solid ratio at two particle sizes is 12.4%, 11%, 14%, and 14.1% for the aggregate particles with densities of 3250, 3500, 3750, and 4000, respectively.

(2) When four groups of aggregate particles with different densities are transported with the grout, the solidification ratio of 4 mm aggregate particle reaches the maximum faster than that of 3 mm aggregate particle in the first and middle period of transport. In the middle and late stages of transport, the solids ratio of 4 mm aggregate particles decreases more rapidly and is even lower than the solids ratio of 3 mm aggregate particle. When the aggregate density is the same, the “vertical settlement force” on a single aggregate particle is only related to the particle size of the aggregate particle; the larger the particle size, the greater the settlement force on it. At the same spatial location, the aggregate particles are subjected to a small difference in “propulsive force,” but the larger the particle size, the greater the “settling force,” so the faster the deposition rate; so, in the first and middle stages of aggregate particle transport, the 4 mm aggregate settles faster, and the measured solid ratio is greater.

Figure 11: Variation of solid ratio of aggregate particles of different particle sizes with grout flow at different densities.
5. Conclusions

(1) The mechanical analysis of individual aggregate particles is carried out, and the mechanical intrinsic model of coupled solid-liquid flow is obtained by combining the flow field theory. Based on the Eulerian bidirectional coupling model, the CFD-DEM numerical model is constructed by coupling FLUENT and EDEM software, and the transport and diffusion law of aggregate with grout in the fracture of rock formation without pressure or low pressure is obtained by numerical simulation.

(2) Through the analysis of 3 mm and 4 mm particle size of different densities of aggregate particles with the grout flow process of aggregate velocity cloud map and volume fraction cloud map, aggregate particles in its transport process are subjected to a variety of settlement forces and gradually deposited; the smaller the particle size, the smaller the density, and the farther the transport distance of aggregate particles; in particle size of 3 mm, the density of 3250 aggregate particle transport distance is as far as 2873 mm. Aggregate particles with a particle size of 4 mm and a density of 4000 have the closest transport distance, which is only 1450 mm; when the aggregate density of both particle sizes changes from 3500 to 3750, the aggregate transport distance decreases significantly.

(3) Combined with the particle velocity cloud map and particle volume fraction cloud map, the change curves of solid ratio and sedimentation ratio during aggregate transportation are shown that the solid ratio of two particle sizes and four densities of aggregates increases and then decreases with their transportation. As the aggregate is gradually deposited by gravity during its transportation, the aggregate concentration ratio decreases gradually. In the first and middle period of aggregate transportation, the deposition of aggregate is greater than the decrease of its concentration; so, the influence of deposition on solid ratio is greater, which is reflected in the gradual increase of solid ratio, while in the middle and late period of aggregate transportation, the concentration of aggregate decreases significantly.

(4) The maximum value of solid comparison of 4 mm aggregate is greater than that of 3 mm aggregate at the same density in the rising stage of solid comparison value; the greater the density at the same particle size, the greater the maximum value of solid comparison of aggregate. The larger the size of the aggregate, the greater the density, and the smaller the transport distance required to reach the maximum value of the solid comparison; in the particle size of 4 mm, the density of 4000 aggregate particles only needs 0.5 m to reach the maximum value of the solid comparison, while in the particle size of 3 mm, the density of 3250 aggregate particles needs to transport 1.25m to reach the maximum value of the solid comparison. Similarly, the larger the particle size and the higher the density of the aggregate, the shorter the transport distance required to reach 100% settlement ratio.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research work in the article was carefully supervised by Cao Zhengzheng (Henan Polytechnic University). And this work was supported by the National Natural Science Foundation of China (U1904128, 52004082), the Natural Science Foundation of Henan Province (222300420007), the Science and Technology Project of Henan Province (222102320004), the Young Teacher Foundation of Henan Polytechnic University (2019XQG-08), the Ph.D. Programs Foundation of Henan Polytechnic University (B2022-25), and the Research and Practice Project of Educational and Teaching Reformation of Henan Polytechnic University (2021JG100).

References


