

Article

Study on the Adhesion Properties of Raw Coal and Adhesive Clogging Characteristics of Underground Coal Bunkers

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Abstract: The automation and continuous operation of coal production are fundamental to the construction of high-yielding and efficient mines. Underground coal bunkers, serving as the pivotal link between various production and transportation segments, are vital for the seamless operation of mines. Nonetheless, the adhesive properties of raw coal can lead to increasingly severe issues, such as the adhesive clogging of coal bunkers. To address this issue, this paper first employs a self-designed raw coal shear testing apparatus to conduct experiments under varying conditions of shear interfaces, moisture content in raw coal, and compaction forces. Obtaining the adhesion behavior characteristics and adhesion parameter variation patterns of raw coal at coal-coal and coal-wall interfaces under various influencing factors. Subsequently, leveraging the adhesion property parameters of raw coal and the engineering conditions of the 1011 roadway coal bunker in Taoyuan Coal Mine II, a numerical model for coal bunker discharge using irregular particles was developed with the PFC2D numerical simulation software. Based on these, we obtained the influence patterns of various factors, such as coal bunker convergence angle, coal storage height, and coal moisture content, on the coal particle flow pattern, bunker wall pressure, and adhesive clogging distribution characteristics of the coal bunker during the discharge process, thereby revealing the mechanisms underlying the adhesive clogging phenomenon. The findings offer significant insights for optimizing solutions to the adhesive clogging issues in underground coal bunkers and ensuring their safe and efficient operation.

Keywords: adhesion properties of raw coal; shear test; coal particle flow pattern; adhesive clogging situation of coal bunker; coal bunker wall pressure



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1. Introduction

As the mechanization of comprehensive coal mining machinery advances and concentrated production in mining areas is realized, the production capacity of mines has been continuously increasing. This progress has raised the bar for the automation and continuity of coal production. Underground coal bunkers, serving as a pivotal nexus connecting various production links in coal mines, are essential for the sustained and efficient operation of the underground transport system [1]. Due to the adhesion properties of raw coal [2–4], combined with the presence of moisture and gangue, promote agglomeration and wall adhesion. This can lead to substantial build-up on bunker walls or even complete blockages [5], which hampers the efficiency of coal bunker utilization and disrupts the

normal flow of production and transportation within the mine. Consequently, research into the adhesion properties of raw coal and the characteristics of adhesive blockages in coal bunkers is of paramount theoretical and practical importance. Such research is fundamental to resolving the issue of adhesive blockages in underground coal bunkers and ensuring their safe and efficient operation.

The adhesion properties of raw coal are critical parameters that characterize its flowability. In coal bunkers, raw coal predominantly exists in particulate form. Currently, numerous experts and scholars have conducted in-depth studies on the adhesion properties between these particles from macroscopic and microscopic perspectives. Mellmann et al. [6] used the Jenike shear test to study the impact of particle shape on adhesion properties and flowability, concluding that particles closer to spherical shapes with greater surface roughness exhibit poorer flowability. Liu et al. [7] examined the influence of brown coal's particle size distribution on its flowability, finding that the cohesion of brown coal is significantly affected by particle size distribution. Chen et al. [8] measured the adhesion property parameters of sawdust, brown coal, and hard coal, determining their flow functions. Sadowski et al. [9] suggested that particle motion involves friction, which is mainly influenced by normal force and the coefficient of friction. Carlevaro et al. [10] and Hartmueller et al. [11] concluded that particle adhesion is dependent on van der Waals forces and liquid bridge forces, proposing a formula to calculate interparticle adhesion force. Samadani [12], Jiao [13,14], and Younes [15] attributed the agglomeration of moist particles to the formation of liquid bridges between water and coal particles, with higher moisture content leading to more liquid bridges and greater difficulty in separating the coal material. The aforementioned studies primarily investigated the adhesion properties between particles by considering factors such as particle shape, size distribution, and moisture content, achieving significant progress. However, these studies predominantly focused on the adhesion behavior of specific types of coal or powdered materials. In contrast, raw coal in coal bunkers typically exists under compaction conditions, and its adhesion properties are not only influenced by the inherent attributes of the particles but are also closely related to the degree of compaction. Additionally, raw coal exhibits a tendency to adhere to the bunker walls, yet studies on the adhesion properties at the coal-wall interface remain insufficient. To comprehensively uncover the true adhesion behavior of underground raw coal, it is essential to systematically investigate the combined effects of factors such as moisture content, compaction level, and interfacial interactions.

Regarding the adhesive clogging problem in bunkers, numerous scholars have also conducted extensive research from various perspectives, including material flow velocity, flow pattern, and bunker wall pressure [16–19]. Among them, Zhu et al. [20,21] divided the stored material inside the bunker into four regions based on the flow state: the mass flow region, the funnel flow region, the transition region between mass flow and funnel flow, and the wall adhesion region. Liu et al. [22] employed a similarity experiment and numerical simulation method to study the flow trend of particles during coal discharge, categorizing the particles inside the bunker into three zones and analyzing the flow characteristics of each zone. Böhrnsen et al. [23] utilized the finite element method (FEM) based on the Eulerian reference system to calculate the deformation rate, velocity field, and stress distribution during bunker discharge. Zhu et al. [24] employed the EDEM program to simulate the coal bunker's discharge process, studying the flow patterns of coal particles and the distribution characteristics of wall pressure. Their findings indicated that coal material could be classified into mass flow and funnel flow patterns, and they explained the transition between these flow patterns and wall pressure distribution based on the arching principle. Ding et al. [25] predicted the material flow mode during discharge using the finite element method and studied the effect of the bunker hopper's inclination angle

on the flow mode. Xu et al. [26], Yang et al. [27], and Zhang et al. [28] utilized the Discrete Element Method (DEM) to explore the impact of particle size and distribution on particle fluidity in silos. Current research primarily focuses on material flow characteristics and bunker wall pressure distribution under specific parameter conditions, while studies on the adhesive clogging characteristics of coal and their influencing factors remain limited. There is a lack of systematic quantitative research on the effects of raw coal moisture content, coal storage height, and coal bunker structural parameters on clogging behavior.

Therefore, this study focuses on raw coal in coal bunkers as the research subject. By independently designing a raw coal shear test system and conducting shear tests, the effects of moisture content, compaction pressure, and interface effects on the adhesion parameters of raw coal are investigated. Based on the adhesion property parameters of raw coal, PFC2D software is employed to quantitatively analyze the influence of moisture content, coal storage height, and coal bunker structural parameters on the adhesive clogging characteristics of coal bunkers. This research aims to reveal the mechanisms of adhesive clogging in underground coal bunkers and provide scientific evidence and valuable guidance for optimizing solutions to this issue.

2. Experimental Study on Adhesion Properties of Raw Coal

2.1. Sample Raw Coal and Testing Equipment

(1) Raw coal parameters

The coal samples selected for this experiment were obtained from the raw coal bunker of the Taoyuan Coal Mine II 1011 mining roadway in the Huaibei mining area of China. An industrial composition analysis of the coal samples was conducted, with the results presented in Table 1. It was determined that the moisture content (w) of the raw coal is approximately 3%. The raw coal was screened to determine its particle size distribution, and the resulting distribution curve is shown in Figure 1. The curve indicates that more than 97% of the raw coal particles have a size range of 0–15 mm. Therefore, particles within this size range were selected for the experimental study.

Table 1. Industrial composition analysis of raw coal.

Test Item	M_{ad} (%)	A_{ad} (%)	V_{daf} (%)	S_{td} (%)	FC_{ad} (%)
Raw coal	2.94	24.18	38.73	0.23	33.92

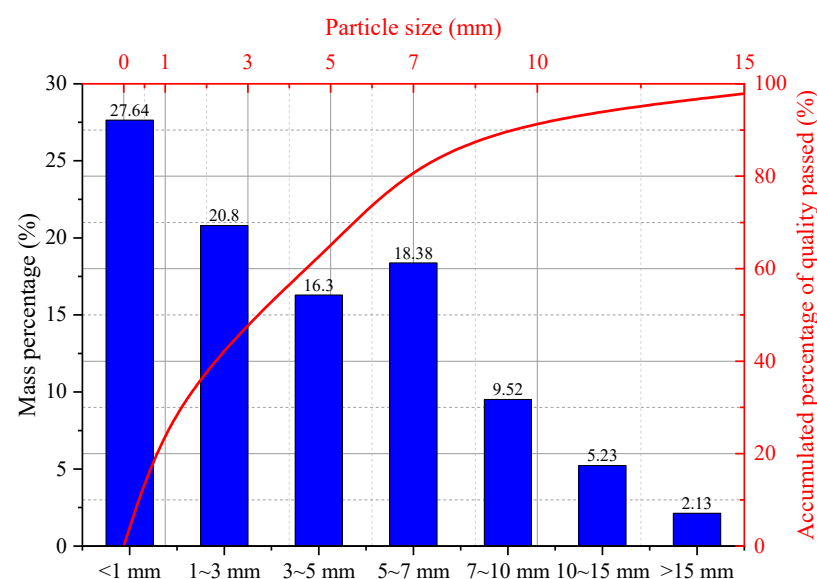


Figure 1. Particle size distribution of raw coal.

(2) Testing equipment

Based on the Jenike shear test principles [29,30], a hydraulic servo-controlled testing machine was employed, for which a specific raw coal shear test mold was designed. This setup formed the raw coal shear testing system used in this experiment. The testing machine consists of a bidirectional independent hydraulic loading servo control system and a data acquisition system. The servo-loading control system includes two independent loading and unloading subsystems that are perpendicular to each other, both utilizing servo-controlled rigid loading methods. The data acquisition system is equipped with stress and displacement sensors, with measurement accuracies of 0.01 kN and 0.002 mm, respectively. The raw coal shear testing device comprises upper and lower L-shaped compression plates, a shear box, and a normal load application plate. Each L-shaped plate has a 90° wedge that ensures the shear plane is fixed at the midpoint of the shear box. The upper L-shaped plate has a reserved hole through which the normal load application plate can pass to exert a normal compaction force on the raw coal inside the shear box.

To investigate different shear interfaces (coal-coal interface, coal-wall interface), we filled the lower shear box with either raw coal or cast C30 concrete (identical to the material of the actual coal bunker walls), respectively. By shearing these different interfaces, we can obtain the adhesion parameters between raw coal particles and between raw coal particles and the bunker wall, as depicted in Figure 2. The raw coal particles were placed in the shear box, and a normal stress was applied with the normal stress subsystem of the testing machine. The L-shaped compression plate, driven by the tangential subsystem, was used to perform horizontal shearing of the raw coal.

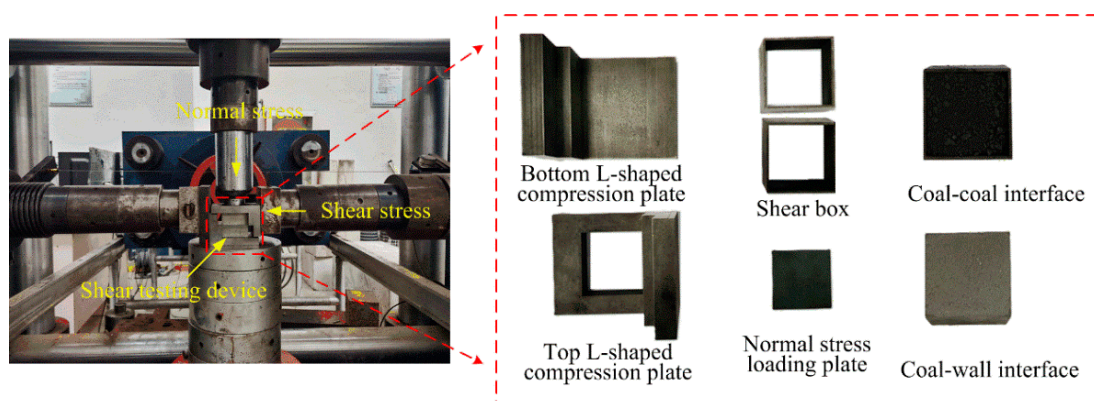


Figure 2. Raw coal shear test system.

2.2. Test Plan and Method

(1) Test plan

The test plan considered the significant impact of moisture content on the flow and cohesion properties of raw coal. Additionally, the height of coal storage in a bunker, which affects the compaction force on the raw coal, has a significant influence on the adhesion characteristics of raw coal. Finally, the adhesion properties between raw coal and bunker walls are important parameters for studying the mechanism of sticky blockage in coal bunkers. Therefore, the experiment focused on the factors of raw coal moisture content (w), compaction force (p), and the two interfaces of coal-coal and coal-wall. Through shear testing of raw coal, the study aimed to understand the variation in adhesion parameters under different influencing factors and shear interfaces.

Based on the measured raw coal parameters, its initial moisture content is approximately 3%. To investigate the effect of moisture content on the adhesion properties of the coal material, we prepared raw coal samples with four moisture contents ($w = 0\%$,

1%, 3%, 5%) using drying and humidification methods. Three levels of compaction force ($p = 300$ kPa, 400 kPa, 500 kPa) were selected, with three sets of normal stresses set for each level of compaction force. In total, 72 sets of experiments were designed for the two interfaces (coal-coal interface and coal-wall interface), with the influencing factors and their levels detailed in Table 2. The correspondence between compaction force and normal stress is shown in Table 3.

Table 2. Influencing factors and their levels.

Factor	Shear Interface	Moisture Content $w/\%$	Compaction Force p/kPa
Level 1	Coal-Coal	0	300
Level 2	Coal-Wall	1	400
Level 3	-	3	500
Level 4	-	5	-

Table 3. Compaction Force and Corresponding Normal Stress.

Compaction Force p/kPa		Normal Stress σ_n/kPa		
300	200	250	300	
400	200	300	400	
500	300	400	500	

(2) Test method

The procedure for operating the raw coal shear testing device is as follows:

① Filling: First, the required raw coal mass for the test was determined to be 120 g based on the volume of the shear box. Subsequently, coal particles within each particle size range were weighed according to the particle size distribution ratio, mixed uniformly, and placed into the shear box, ensuring a continuous and uniform filling process to prevent the formation of easily shearable layers within the coal sample due to interrupted filling.

② Compaction: After filling, place the normal load application plate on top and apply a controlled stress to reach the set compaction force, maintaining stability.

③ Pre-shearing: Use a displacement-controlled loading mode to shear the coal material in the shear box at a rate of 0.24 mm/min. Stop shearing when the shear stress stabilizes.

④ Shearing: Change the normal stress to the predetermined value and resume shearing in displacement-controlled loading mode at a rate of 0.24 mm/min. Stop the test and record the shear stress data when the shear stress reaches its maximum or a stable state.

2.3. Research Results and Discussion

2.3.1. Calculation of Raw Coal Adhesion Properties

Based on the designed test plan and method, typical post-pre-shear stress-displacement curves for raw coal were obtained, as shown in Figures 3 and 4. The curves reveal that the shear stress-displacement behavior for both coal-coal and coal-wall interfaces is fundamentally similar. In the initial shearing phase, shear stress increases gradually, which is attributed to the incomplete formation of contact points between coal particles and the adjustment and rearrangement of particles. As the shear displacement continues to grow, the shear stress rises rapidly and exhibits irregular fluctuations. This phenomenon is related to the diversity of raw coal particles, localized particle breakage, variations in interface friction, and the complex mechanical transmission paths between particles. Eventually, the shear stress stabilizes, and the coal material reaches its limit stress state, at which point the contact forces or interface forces between coal particles achieve equilibrium. Furthermore, the experiments demonstrated that shear strength increases significantly with higher moisture content and normal stress. This finding suggests that the enhancement of liquid

bridge forces and normal stress contributes to the bonding and friction effects at particle contact surfaces.

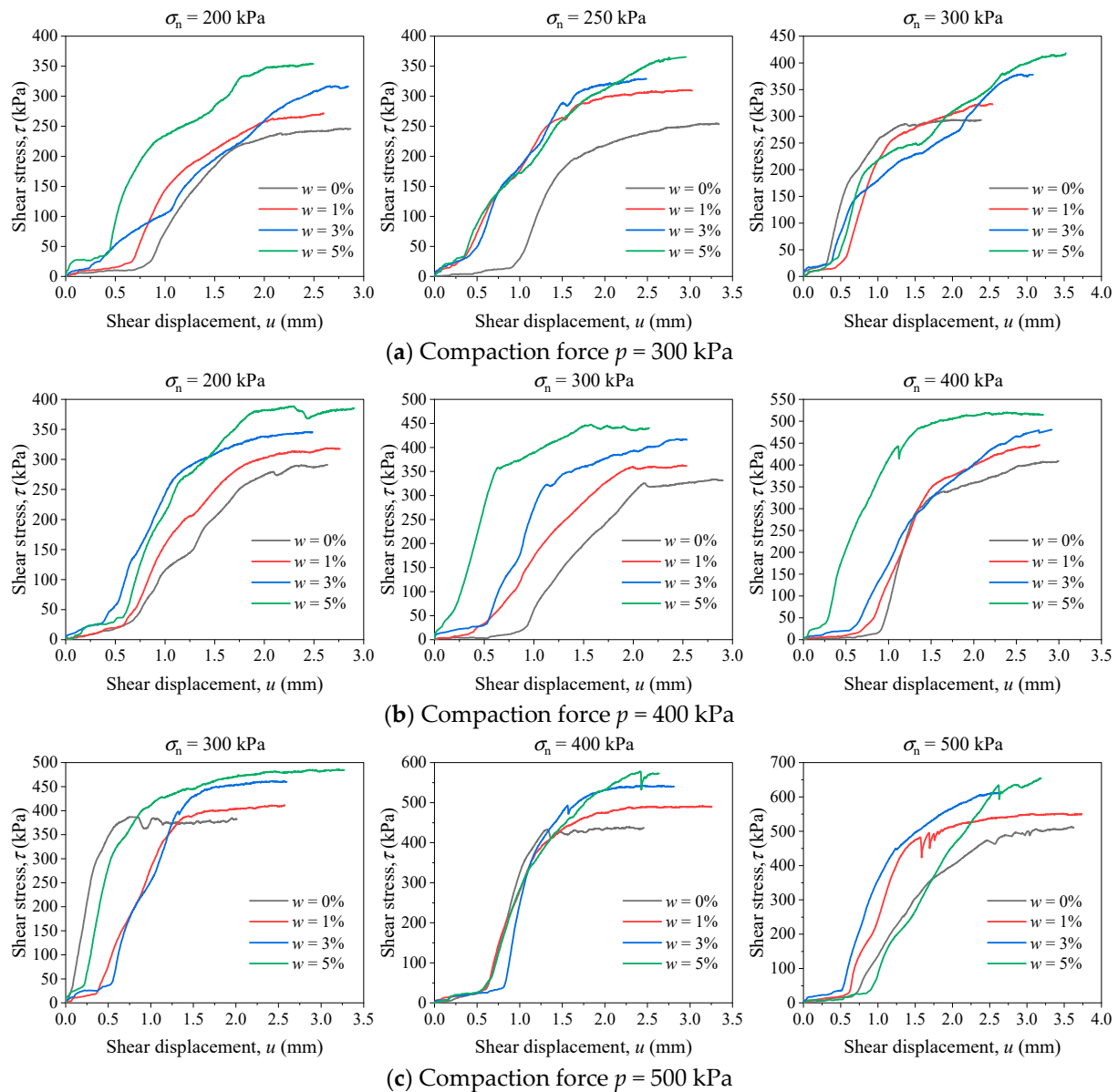


Figure 3. Relationship curves for the coal-coal interface under different conditions.

The compacted raw coal and the coal at a fixed depth within the coal bunker exhibit the same mechanical characteristics. Their shear yield trajectory is composed of shear failure points under various normal forces. Raw coal under the same compaction force shares an identical shear yield trajectory. As depicted in Figure 5, a linear fit of the three shear yield points A, B, and C yields the shear yield trajectory for the compacted raw coal, providing parameters that characterize the adhesion properties of raw coal. The shear yield behavior of raw coal adheres to the Mohr-Coulomb criterion [31,32].

$$\tau = \sigma_n \tan \varphi + c \quad (1)$$

where τ is the shear strength (kPa), σ_n is the normal stress (kPa), φ is the internal friction angle of raw coal ($^\circ$), and c is the cohesion of raw coal (kPa).

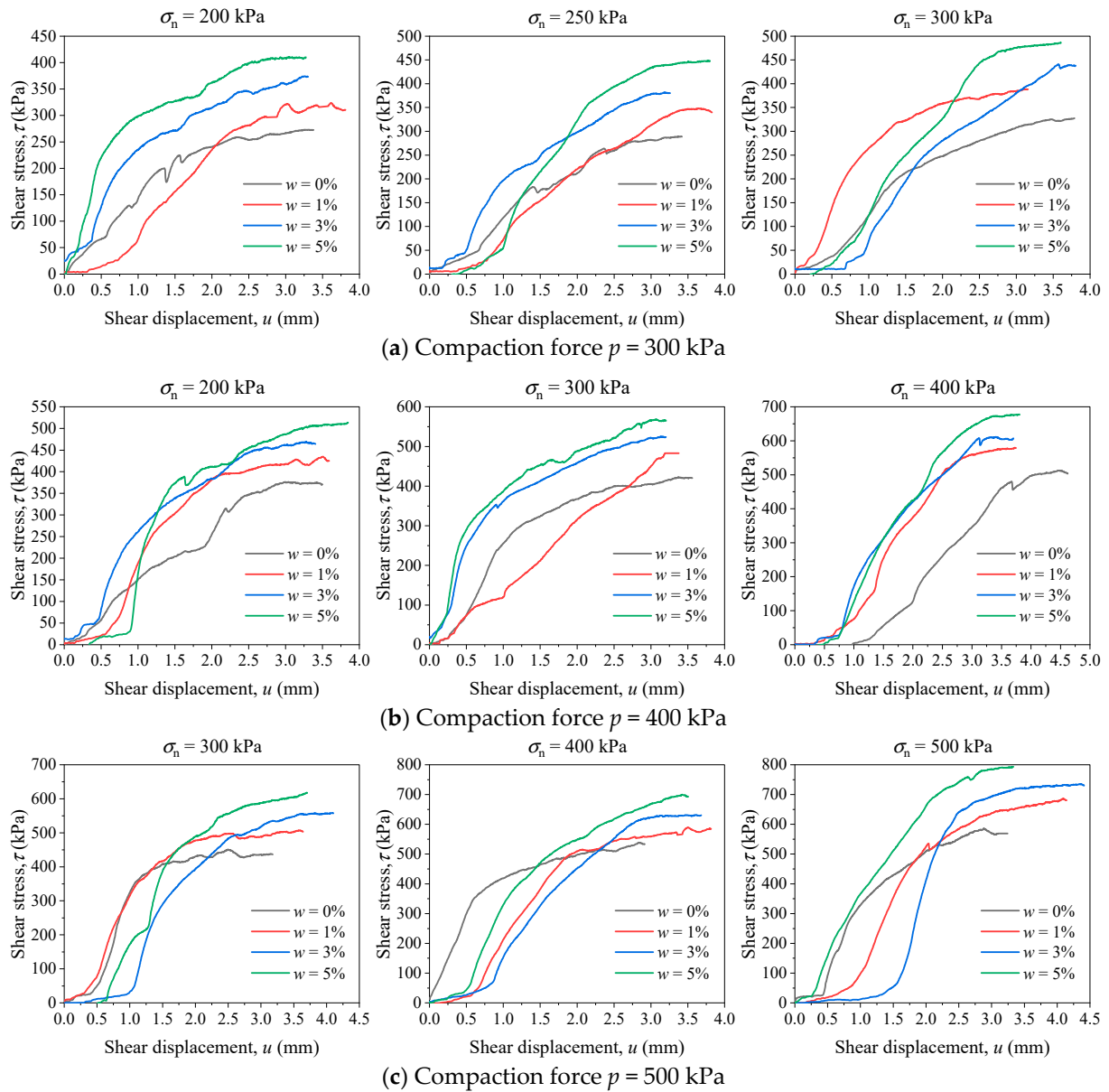


Figure 4. Relationship curves for the coal-wall interface under different conditions.

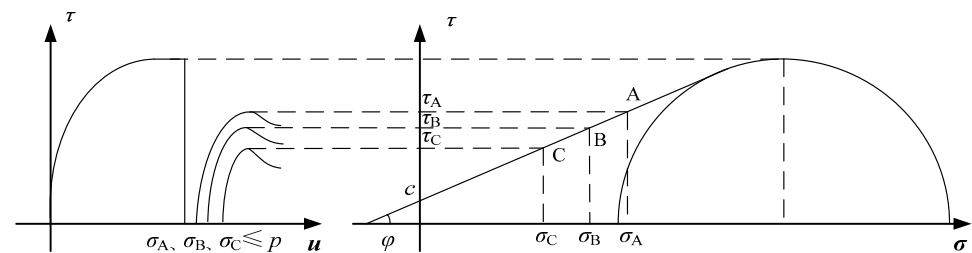


Figure 5. Principle of raw coal shear test.

Linear fitting was performed on the results of the raw coal shear test, yielding fitting curves for different compaction forces and moisture contents at the coal-coal and coal-wall interfaces, as shown in Figures 6 and 7. The correlation coefficients R^2 of these fitting curves all exceed 98%, indicating a high quality of fit. Using these curves, the cohesion and internal friction angle of raw coal under various conditions at the two interfaces were calculated, as presented in Tables 4–7.

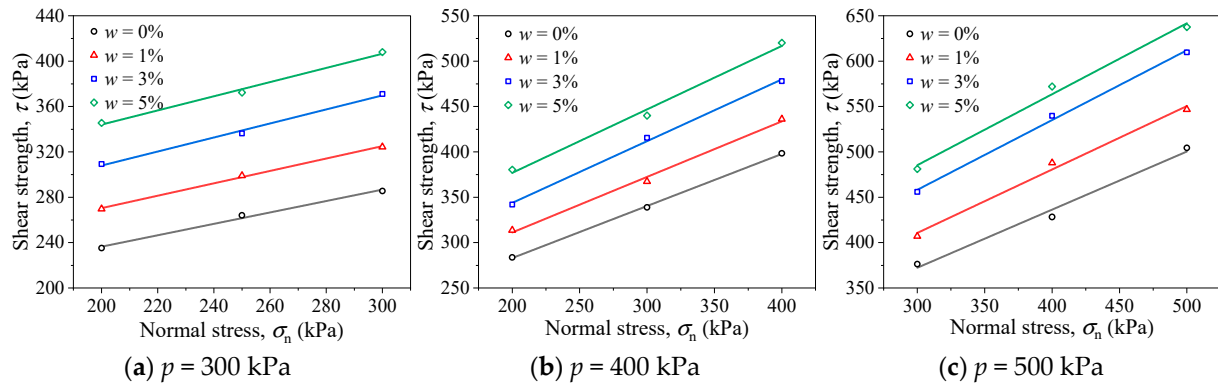


Figure 6. Fitting curves for the shear test results of the coal-coal interface.

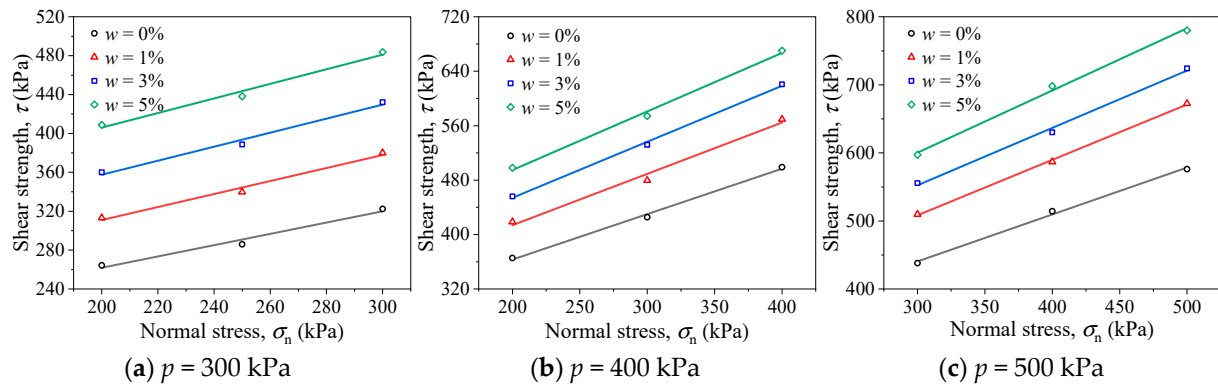


Figure 7. Fitting curves for the shear test results of the coal-wall interface.

Table 4. Cohesion for Coal-Coal Interface.

$p \backslash w$	0%	1%	3%	5%
300 kPa	138.488 kPa	161.308 kPa	183.5 kPa	217.748 kPa
400 kPa	166.756 kPa	186.44 kPa	207.684 kPa	237.04 kPa
500 kPa	180.144 kPa	200.888 kPa	227.424 kPa	250.668 kPa

Table 5. Internal Friction Angle for Coal-Coal Interface.

$p \backslash w$	0%	1%	3%	5%
300 kPa	26.54°	28.66°	31.85°	32.16°
400 kPa	30.02°	31.65°	34.24°	34.97°
500 kPa	32.64°	34.97°	37.57°	38.04°

Table 6. Cohesion for Coal-Wall Interface.

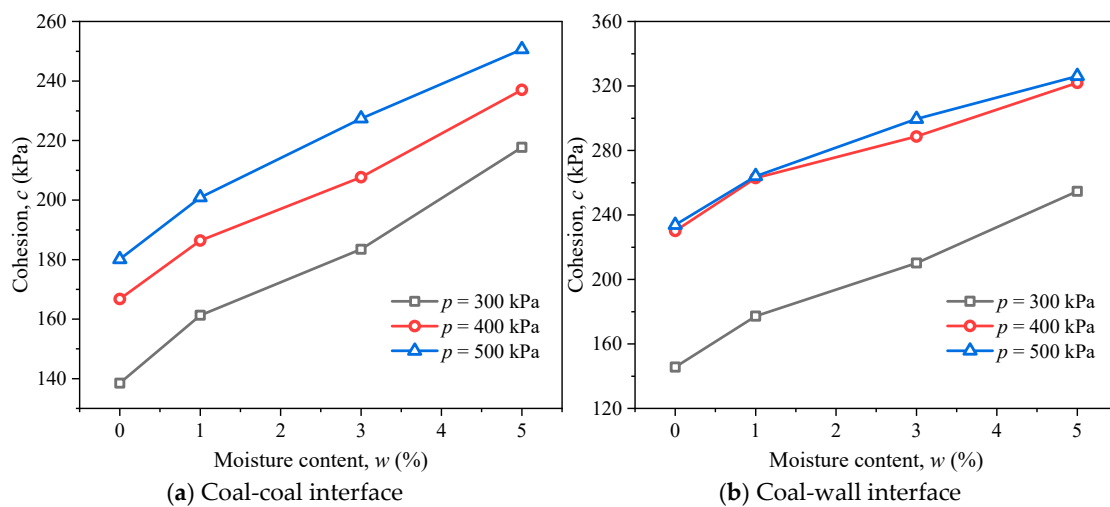
$p \backslash w$	0%	1%	3%	5%
300 kPa	145.7 kPa	177.28 kPa	210.192 kPa	254.68 kPa
400 kPa	230.132 kPa	262.964 kPa	288.684 kPa	321.956 kPa
500 kPa	233.836 kPa	264.044 kPa	299.556 kPa	326.084 kPa

Table 7. Internal Friction Angle for Coal-Wall Interface.

$p \backslash w$	0%	1%	3%	5%
300 kPa	30.15°	33.76°	36.14°	36.87°
400 kPa	33.44°	37.02°	39.60°	40.78°
500 kPa	35.38°	39.16°	41.25°	42.43°

2.3.2. Influence of Moisture Contents on Raw Coal Adhesion Properties

As a crucial parameter reflecting the adhesive properties of raw coal, the cohesion of raw coal represents the ultimate shear stress at the interface when the normal stress is zero. Figure 8 illustrates how the cohesion at the coal-coal and coal-wall interfaces changes with moisture content.

**Figure 8.** Effect of moisture content on cohesion of raw coal.

The figure indicates that cohesion at both interfaces increases with rising moisture content. This trend is attributed to the fact that at lower moisture levels, water is primarily present as adsorbed water between coal particles. This adsorbed water forms liquid bridges and generates negative pressure at the interfaces, which together promote the agglomeration of coal particles. As moisture content increases, more liquid bridges form, enhancing the cohesion of raw coal. Additionally, the contact between coal particles and the bunker wall is more substantial than between coal particles themselves, resulting in the coal-coal interface having lower cohesion than the coal-wall interface under the same compaction force and moisture content.

Figure 9 presents the variation in internal friction angles at the two interfaces with different moisture contents. It is observed that the internal friction angles increase with moisture content, but the rate of increase diminishes, indicating a decreasing influence of moisture content on the internal friction angle of raw coal. For example, at a compaction force of 300 kPa on the coal-wall interface, the internal friction angle increases by approximately 3.6° when moisture content goes from 0% to 1%. However, an increase in moisture content from 3% to 5% results in only about a 0.7° rise in the internal friction angle. At lower moisture levels, contact between coal particles is primarily through friction. As moisture content increases, adsorbed water fills the gaps between particles, leading to increased contact between smaller and larger particles and a consequent rise in the internal friction angle. Yet, as moisture content continues to grow, the lubricating effect of the adsorbed water between interfaces starts to reduce the impact on the internal friction angles.

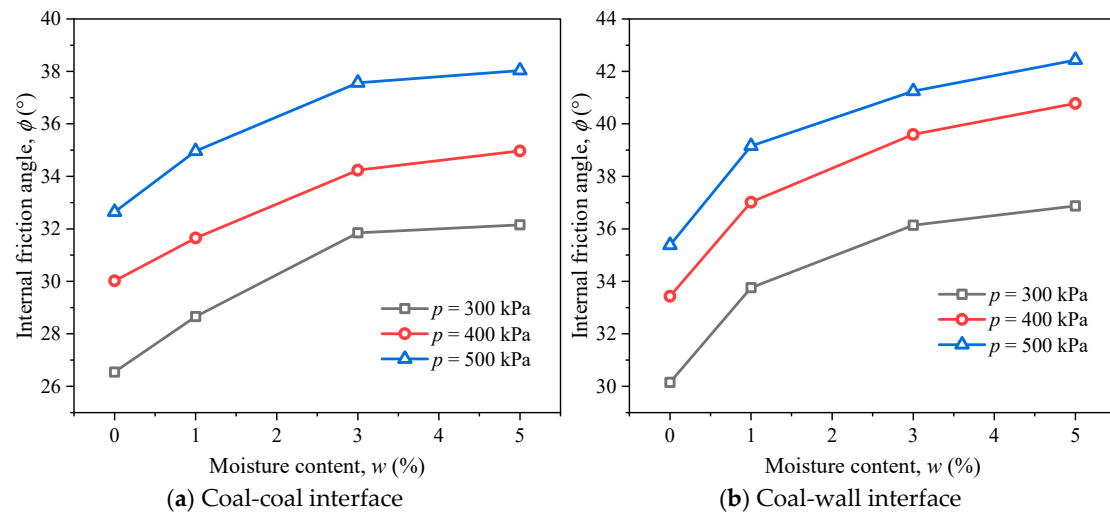


Figure 9. Variation of raw coal internal friction angles with respect to moisture content.

2.3.3. Influence of Compaction Force on Raw Coal Adhesion Properties

Figure 10 shows the changes in cohesion at the coal-coal and coal-wall interfaces under varying compaction forces. The results indicate that cohesion increases with compaction force at both interfaces, with the coal-wall interface consistently exhibiting higher cohesion than the coal-coal interface under the same conditions. Taking raw coal with a 3% moisture content as an example, for every 100 kPa increase in compaction force, the cohesion at the coal-coal interface rises by about 9.5%, displaying an almost linear trend. However, the increase in cohesion at the coal-wall interface is different; a rise in compaction force from 300 kPa to 400 kPa results in a 37.3% increase in cohesion, but a further increase to 500 kPa only yields a 3.8% increase. This pattern is due to the interlocking of coal particles under compaction, which becomes tighter as compaction force increases, leading to a consistent rise in cohesion at both interfaces. The coal-coal interface, with its numerous voids between particles, requires a greater compaction force for adherence, making its cohesion more sensitive to compaction force. In contrast, the smoother surface of the coal bunker wall allows for better adhesion at the coal-wall interface; thus, as compaction force continues to rise, its influence on cohesion gradually decreases.

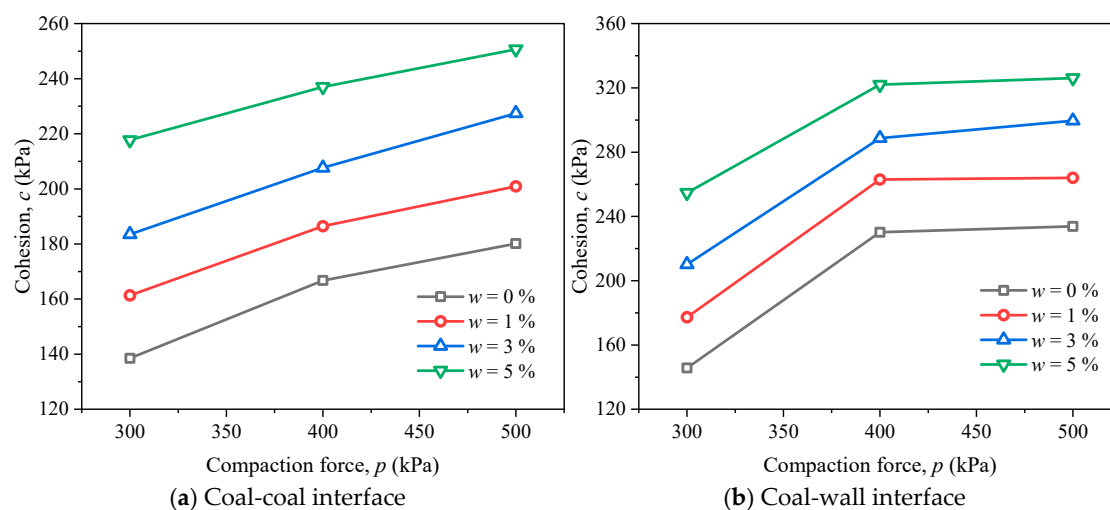


Figure 10. Variation of raw coal cohesion with respect to compaction force.

Figure 11 depicts the changes in internal friction angle at the two interfaces under different compaction forces. The internal friction angle at both interfaces shows a similar

trend of gradual increase with compaction force, and the coal-wall interface has a consistently higher internal friction angle than the coal-coal interface under the same conditions. For raw coal with a 1% moisture content, an increase in compaction force from 300 kPa to 400 kPa results in a 3° rise in the internal friction angle at the coal-coal interface and a 3.3° rise at the coal-wall interface. Higher compaction forces lead to tighter interfacial contact, and with low moisture content, dry friction contributes to the increase in the internal friction angle.

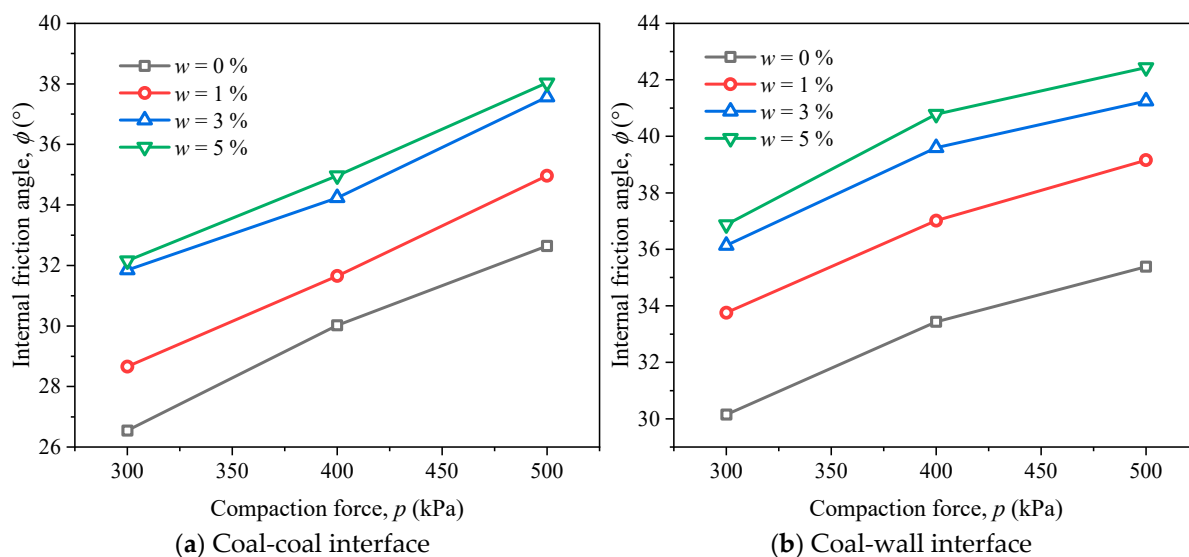


Figure 11. Variation of raw coal internal friction angle with respect to compaction force.

3. Investigation of Adhesive Clogging Characteristics in Underground Coal Bunkers

In practical engineering, due to the complexity of the mechanics of engineering structures and coal materials, it is difficult to effectively guide engineering problems solely based on theory and indoor experiments. Therefore, this paper establishes numerical models for coal storage and unloading in bunkers under different conditions using PFC2D software, based on the adhesion characteristic parameters of raw coal and the engineering conditions of the 1011 roadway coal bunker at Taoyuan Coal Mine II. The models are used to comparatively analyze the flow characteristics of coal materials during the unloading process, the pressure distribution on the bunker walls, and the adhesive clogging characteristics of the coal bunker after unloading. This analysis aims to reveal the mechanism of adhesive clogging in coal bunkers by studying the influence of various factors on adhesive clogging.

3.1. Acquisition and Construction of Raw Coal Particle Contours

To closely replicate the actual conditions of raw coal in the bunker, 140 typical samples of raw coal particles were randomly selected from the site, as shown in Figure 12a. Their shapes were captured using a digital camera, and their contours were extracted, as shown in Figure 12b. These contours were input into PFC to generate clump templates and establish a raw coal particle contour library. During particle generation, clump particle templates were randomly called from this library to create irregular particles with a particle size of 0–15 mm according to the particle size distribution ratio.

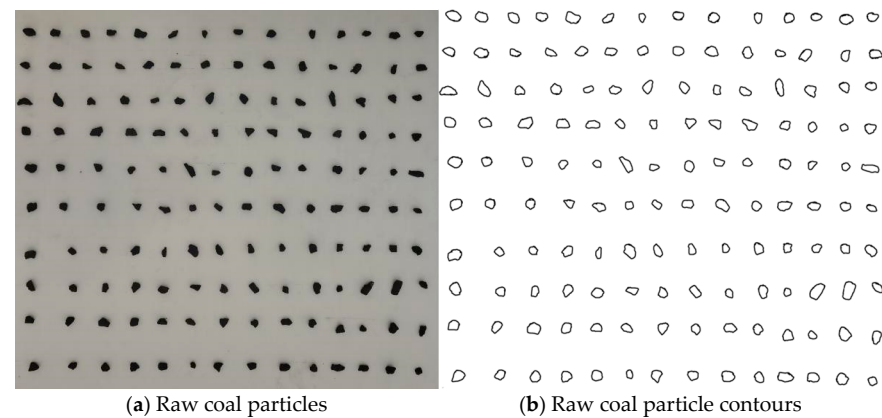


Figure 12. Extraction of raw coal particle contours.

3.2. Numerical Calculation Model and Simulation Method

(1) Numerical model

The main body of the coal bunker in the II 1011 roadway of Taoyuan Coal Mine is cylindrical in shape, with a diameter of 3.1 m, a bottom opening diameter of 1 m, a total height of 28.39 m, a cylindrical segment height of 26.57 m, and a bottom conical segment height of 1.82 m. In the simulation, the linear parallel bond model [33] was used to represent the constitutive relationship between raw coal particles. Due to limitations in computational power, the simulation increased the gravitational density of the particle model by tenfold to simulate a gravity field similar to that of the actual coal bunker. The mechanical parameters for the interactions between coal particles and between particles and the wall were obtained through experiments, with key parameters listed in Table 8.

Table 8. Physical and mechanical parameters of particles obtained using the discrete element model.

Particle Unit Model	Density (kg/m ³)	Particle-Particle Friction Coefficient	Particle-Wall Friction Coefficient	Wall Normal Stiffness (N/m)	Wall Shear Stiffness (N/m)	Particle Normal Stiffness (N/m)	Particle Shear Stiffness (N/m)
Raw coal particles	1500×10	0.65	0.5	3.5×10^6	1.75×10^6	1.75×10^6	0.875×10^6

(2) Simulation of the coal storage process in the bunker

Before discharging, all coal particles must be loaded into the bunker, and the model must reach a stable state before proceeding to the next simulation step. A layer-by-layer particle generation method was used: 4000 coal particles were generated at the top of the bunker, allowed to fall freely as shown in Figure 13a, and reached equilibrium after some time as shown in Figure 13b. This process was repeated layer by layer until the bunker was filled to the specified height, as shown in Figure 13c–f.

(3) Simulation of the coal bunker discharge process

After completing the coal storage process, a “receiving bunker” was formed below the bunker outlet with three wall segments using the coal bunker unloading subroutine, and the barrier wall at the outlet was removed, allowing particles to flow out under gravity until equilibrium was reached inside the bunker. The proportion of adhesive coal and the morphology of clogging were recorded at equilibrium, with real-time monitoring of dynamic wall pressure. Since adhesive coal was mainly concentrated at the discharge outlet and the middle-to-lower straight cylinder wall, and the bunker was symmetrical, the analysis focused on the side walls with more adhesive coal, namely wall units 1–10 and 21–30, as shown in Figure 14a. Figure 14b–e show the movement of coal particles during discharge at a storage height of 5 m and the condition of adhesive coal after unloading.

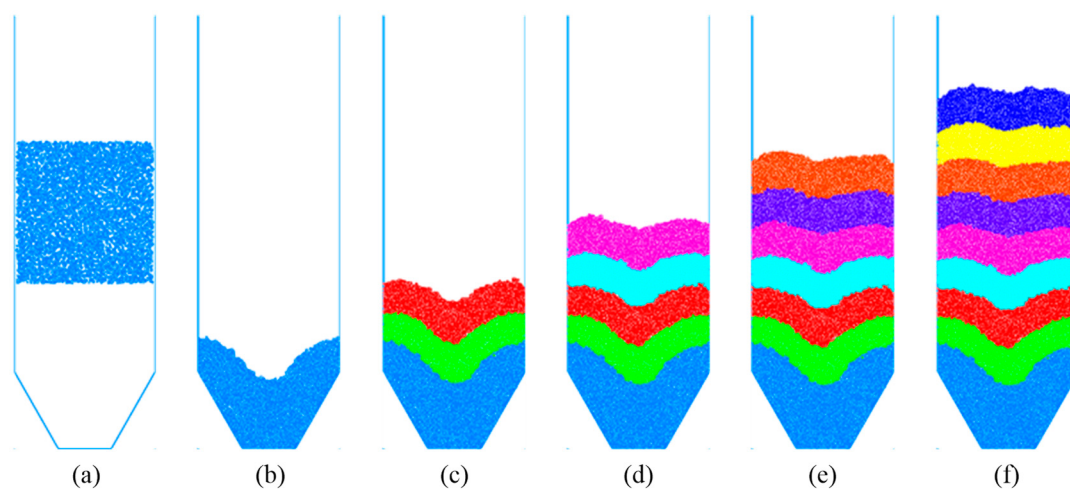


Figure 13. Simulation of the coal storage process in the coal bunker: (a) free fall of coal particles; (b–f) represent the generation of the 1st, 3rd, 5th, 7th, and 9th layers of particles, respectively.

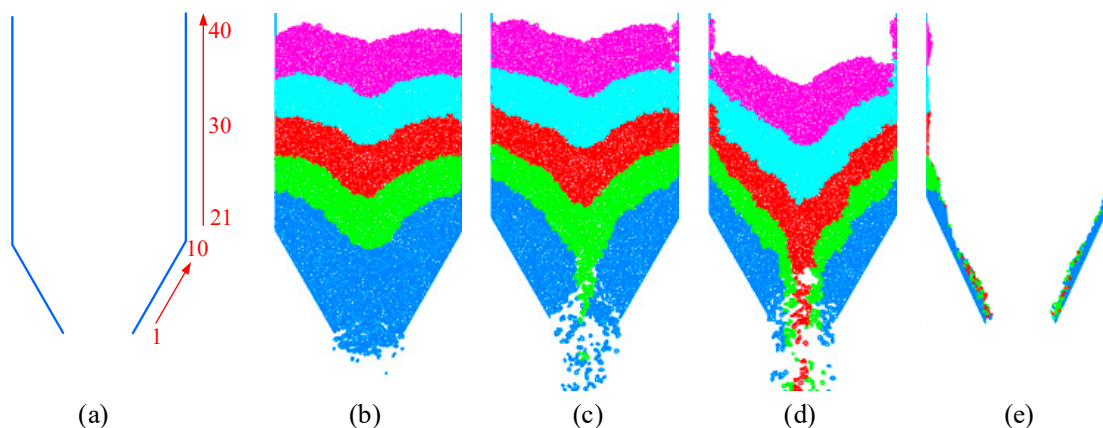


Figure 14. Simulation of the coal bunker discharge process: (a) arrangement of coal bunker wall units; (b–e) represent different stages of the discharge process, respectively.

The figures show that the flow of coal particles inside the bunker exhibits central flow characteristics. Coal in the center moves downward first and quickly, while coal near the walls moves slower due to greater pressure, forming a “V” shape within the bunker. Ultimately, coal adheres to the wall due to the combined effects of friction and adhesion, consistent with real-world engineering, validating the simulation method.

3.3. Analysis of Adhesive Clogging Characteristics of the Coal Bunker

Based on the numerical model and simulation method, three factors were selected for quantitative analysis of adhesive clogging characteristics using a single-factor analysis method: the bunker convergence angle α , raw coal moisture content w , and coal storage height h .

3.3.1. Influence of Convergence Angle on Adhesive Clogging of Coal Bunker

(1) Coal flow characteristics

The study simulated and analyzed five different bunker convergence angles α (50° , 55° , 60° , 65° , 70°) at a coal storage height of 7 m and a raw coal moisture content of 1%. Figure 15 shows the discharge flow velocity characteristics at different convergence angles.

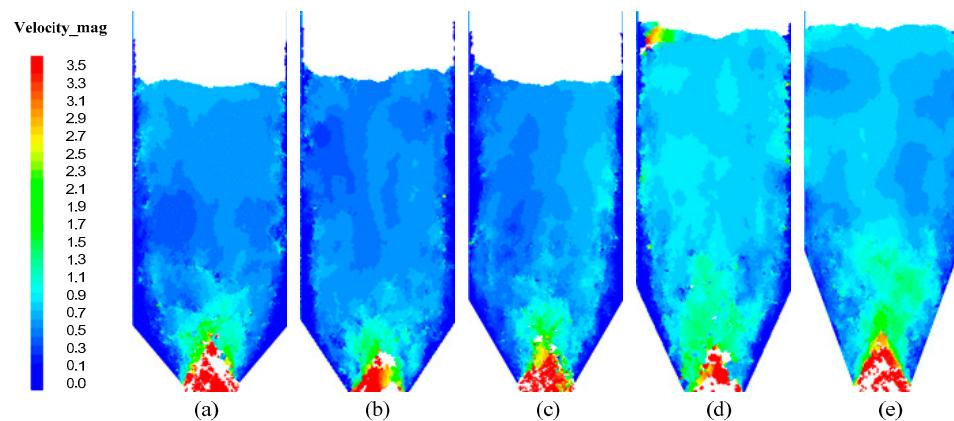


Figure 15. Coal flow velocity distribution at different coal bunker convergence angles: (a) $\alpha = 50^\circ$; (b) $\alpha = 55^\circ$; (c) $\alpha = 60^\circ$; (d) $\alpha = 65^\circ$; (e) $\alpha = 70^\circ$.

As illustrated in Figure 15, as the coal bunker convergence angle α increases, the coal flow velocity gradually increases, and the flow pattern undergoes significant changes. When $\alpha = 50^\circ$ and 55° , the coal particles inside the bunker exhibit slow flow velocities, with a substantial amount of coal near the bunker wall having a flow velocity close to zero, displaying a typical central flow pattern. When $\alpha = 60^\circ$, the coal flow velocity inside the coal bunker noticeably increases, and the flow pattern transitions from central flow to funnel flow. When $\alpha = 65^\circ$, the coal flow velocity inside the bunker increases significantly, and the overall flow pattern becomes more akin to mass flow. When $\alpha = 70^\circ$, the coal material flows downward uniformly, maintaining a high flow velocity, with the overall flow pattern distinctly exhibiting the characteristics of mass flow.

(2) Adhesive clogging situation of coal bunker

Figure 16 illustrates the adhesive clogging situation in the coal bunker at different convergence angles. When α is in the range of 50° to 65° , multiple layers of coal accumulate inside the coal bunker (i.e., the upper layer of coal flows out before the lower layer, and some coal adhere to the inside of the bunker), which is also consistent with the characteristics of central flow. However, when $\alpha = 70^\circ$, the coal bunker is primarily covered with coal adhering to the wall, which is mostly distributed in the order of coal storage, aligning with the adhesive clogging characteristics of a mass flow coal bunker.

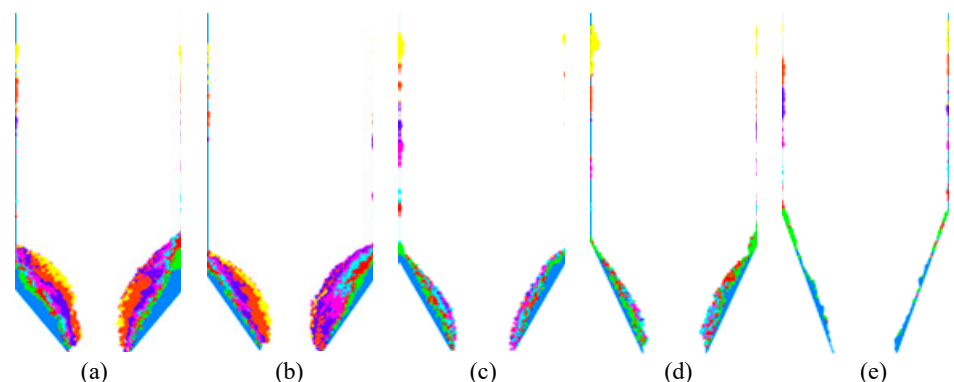


Figure 16. Adhesive clogging situation of coal bunker at different convergence angles: (a) $\alpha = 50^\circ$; (b) $\alpha = 55^\circ$; (c) $\alpha = 60^\circ$; (d) $\alpha = 65^\circ$; (e) $\alpha = 70^\circ$.

Figure 17 depicts the curve of the mass fraction of adhered coal as a function of the convergence angle α . It is observable that as α increases, the mass fraction of adhered coal inside the bunker gradually diminishes. When α is 50° and 55° , the mass fraction of adhered coal in the coal bunker is 12.57% and 10.11%, respectively. When α is 60° and 65° , this

fraction decreases to 5.15% and 3.91%, respectively, indicating a significant improvement in the coal adhesion situation inside the coal bunker. When α is 70° , this fraction further decreases to 1.86%, which is due to the change in the coal flow pattern inside the coal bunker as the mass flow of coal results in only a small portion of coal adhering to the bunker wall.

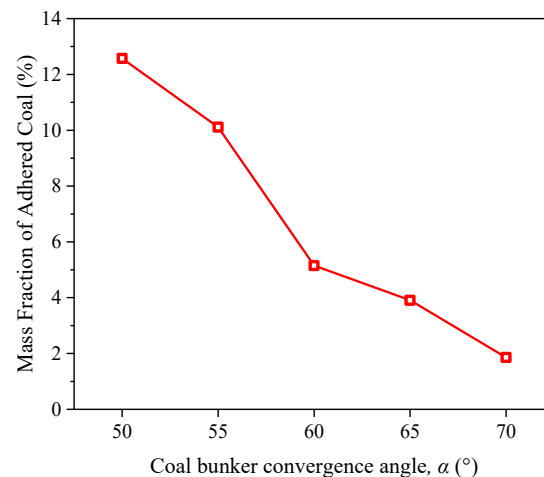


Figure 17. Curve of mass fraction of adhered coal in coal bunker as a function of convergence angle.

(3) Pressure distribution on the coal bunker wall

Based on the adhesive clogging conditions in the coal bunker, we analyzed the pressure at four locations on the bunker walls: wall-1 at the coal bunker discharge outlet, wall-5 in the middle of the coal bunker hopper, and wall-10 and wall-21 at the junction between the hopper and the vertical section. Figure 18 shows the pressure variation curves at these four locations. As depicted in Figure 18a, at the coal bunker discharge outlet (wall-1), there are frequent collisions between coal particles and the bunker wall, resulting in significant fluctuations and lower wall pressure, which makes coal agglomeration and adhesion less likely. Figure 18b–d illustrate the walls where sticky coal is more prevalent. At these locations, the wall pressure quickly rises to a peak at the onset of discharge and then gradually decreases with fluctuations. A comparison of the pressure curves for wall-5, wall-10, and wall-21 reveals that the pressure on the hopper walls is notably higher than on the vertical walls, with the highest pressure occurring in the middle of the hopper, indicating a higher likelihood of adhesive clogging.

Comparing the dynamic wall pressure changes during the discharge process at different coal bunker hopper angles reveals that the larger the hopper angle α , the faster the wall pressure decreases. Additionally, the steady-state wall pressure values suggest that as α increases, the pressures on the walls gradually diminish, reducing the contact force between the wall and the coal particles, thus making coal less likely to stick to the walls. Therefore, increasing the coal bunker hopper angle can effectively control adhesive clogging. However, it should be noted that with larger angles, the coal flow rate increases, making the discharge process more difficult to control and potentially less safe.

Based on the above analysis, when α is 60° , the coal flow is more efficient, the adhesive clogging situation of the coal bunker is significantly improved, and the dynamic wall pressure is relatively stable, ensuring the safe and efficient operation of the coal bunker. Therefore, we consider 60° to be a suitable coal bunker convergence angle (subsequent simulations in this study are also based on $\alpha = 60^\circ$).

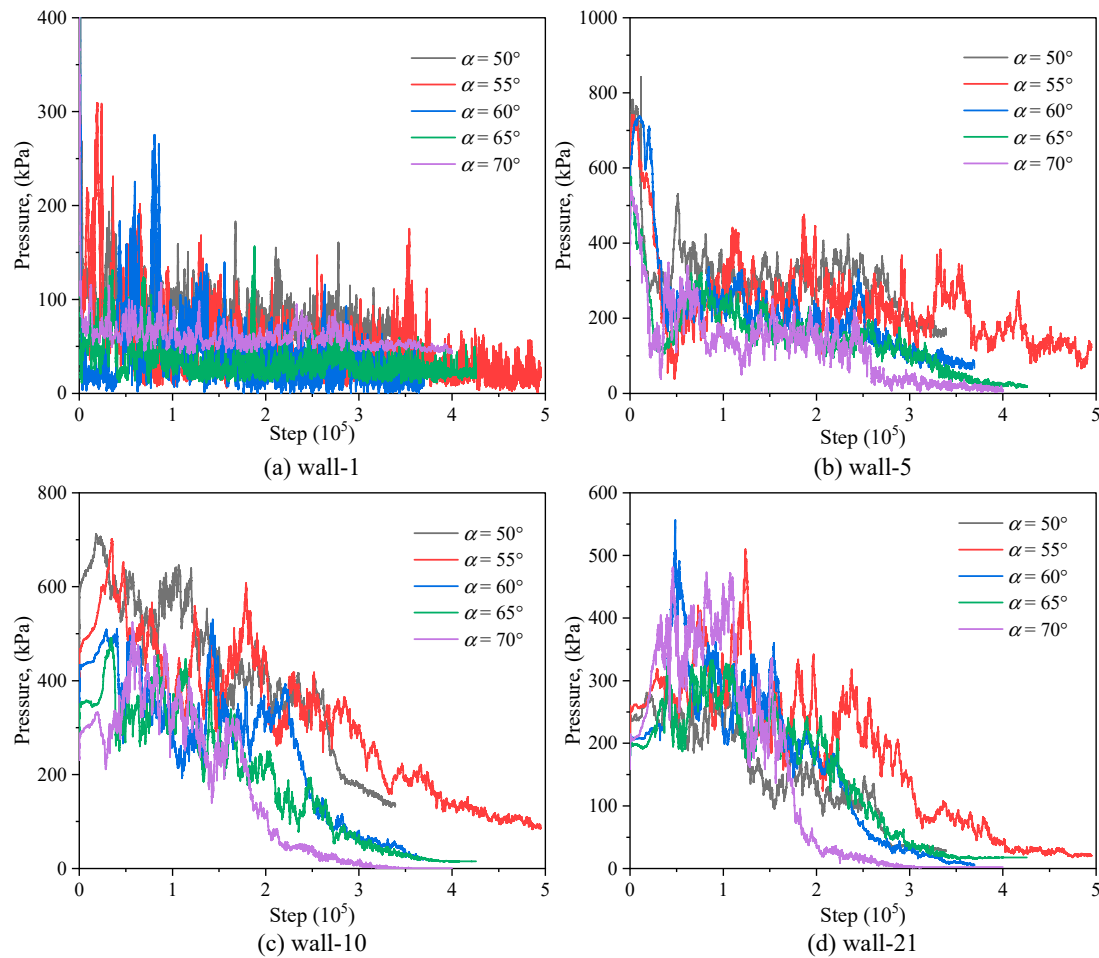


Figure 18. Dynamic wall pressure changes during the discharge process at different coal bunker convergence angles.

3.3.2. Influence of Raw Coal Moisture Content on Adhesive Clogging in Coal Bunker

(1) Coal flow characteristics

This study conducted simulations under conditions of a coal storage height of 5 m and a bunker hopper angle of 60° , with varying raw coal moisture contents of $w = 0\%$, 1% , 3% , and 5% . Figure 19 presents the characteristics of coal discharge flow velocity under different moisture content conditions.

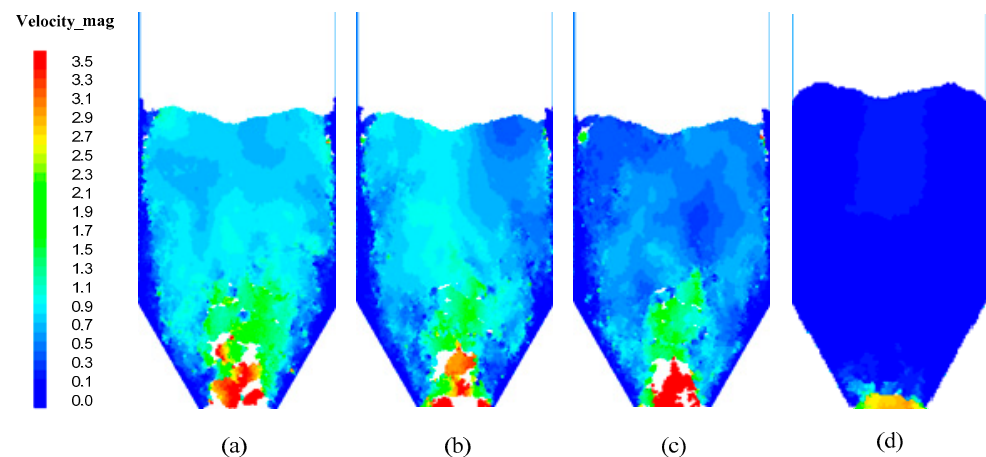


Figure 19. Coal flow velocity distribution under different raw coal moisture content conditions: (a) $w = 0\%$; (b) $w = 1\%$; (c) $w = 3\%$; (d) $w = 5\%$.

From this figure, it can be observed that the raw coal moisture content has a significant impact on the coal flow characteristics. When $w = 0\%$, except for a small amount of coal adhering to the wall, the overall flow velocity of the coal is relatively high, exhibiting mass flow characteristics. When $w = 1\%$ and 3% , the coal flow velocity decreases, and low-velocity adhered coal appears near the bunker wall, with a high-velocity channel forming in the center of the bunker. The coal flow pattern transitions from mass flow to central flow, which is due to the increased moisture content enhancing the adhesion of the coal, leading to a higher flow velocity in the center as the coal in the center is less affected than the coal near the bunker wall. When $w = 5\%$, only the coal at the discharge outlet loses support and flows out of the coal bunker, while the flow velocity of the remaining coal is close to zero, resulting in an arching blockage.

(2) Adhesive clogging situation of coal bunker

Figure 20 illustrates the adhesive clogging situation of the coal bunker at different raw coal moisture contents. When $w = 0\%$, the adhered coal in the coal bunker is distinctly layered, conforming to the mass flow characteristic. When $w = 1\%$, a small portion of the upper layer of adhered coal mixes with the bottom layer, causing the coal flow pattern to transition to central flow. When $w = 3\%$, a substantial amount of mixed adhered coal is observed, which is more consistent with the characteristics of central flow. The simulation test results of coal bunker adhesive clogging can be correlated with the coal bunker flow pattern characteristics depicted in Figure 20.

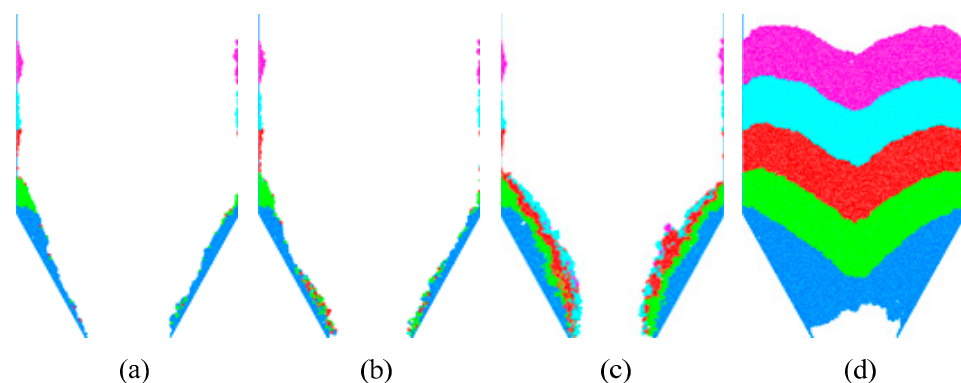


Figure 20. Adhesive clogging situation of coal bunker under different raw coal moisture content conditions: (a) $w = 0\%$; (b) $w = 1\%$; (c) $w = 3\%$; (d) $w = 5\%$.

Figure 21 depicts the curve of the mass fraction of adhered coal in the coal bunker as a function of raw coal moisture content. It can be observed that as the moisture content w increases, the fraction of adhered coal in the coal bunker exhibits an exponential growth trend. When $w = 0\%$, 1% , there is only a small amount of adhered coal in the coal bunker, with mass fractions of 5.76% and 6.31% , respectively. When $w = 3\%$, the amount of adhered coal in the coal bunker increases significantly, with the mass fraction increasing to 17.97% , more than triple the value at lower moisture contents, and a substantial amount of coal agglomeration occurs inside the bunker. When $w = 5\%$, an arching blockage occurs in the coal bunker, and the mass fraction of adhered coal reaches 98.26% . These findings demonstrate that the raw coal moisture content has a significant impact on the coal flow, and coal with higher moisture content is more prone to causing adhesion and increasing the risk of blockage in the coal bunker.

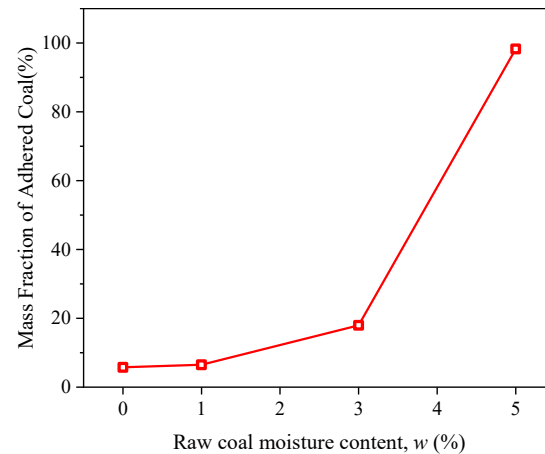


Figure 21. Mass fraction of adhered coal in coal bunker as a function of raw coal moisture content.

(3) Pressure distribution on the coal bunker wall

The dynamic wall pressure variation curves in Figure 22 show that wall pressure changes with moisture content correspond to the bunker's adhesive clogging conditions. When $w = 0\%$ and 1% , the wall pressure curves of the coal are similar, with closely related adhesive clogging situations. When $w = 3\%$, the peak wall pressure is relatively high, facilitating coal adhesion to the wall, and thus the amount of adhered coal increases significantly. When $w = 5\%$, an arching blockage occurs in the coal bunker, which stabilizes shortly after the discharge begins, and the wall pressure remains predominantly static without a significant peak.

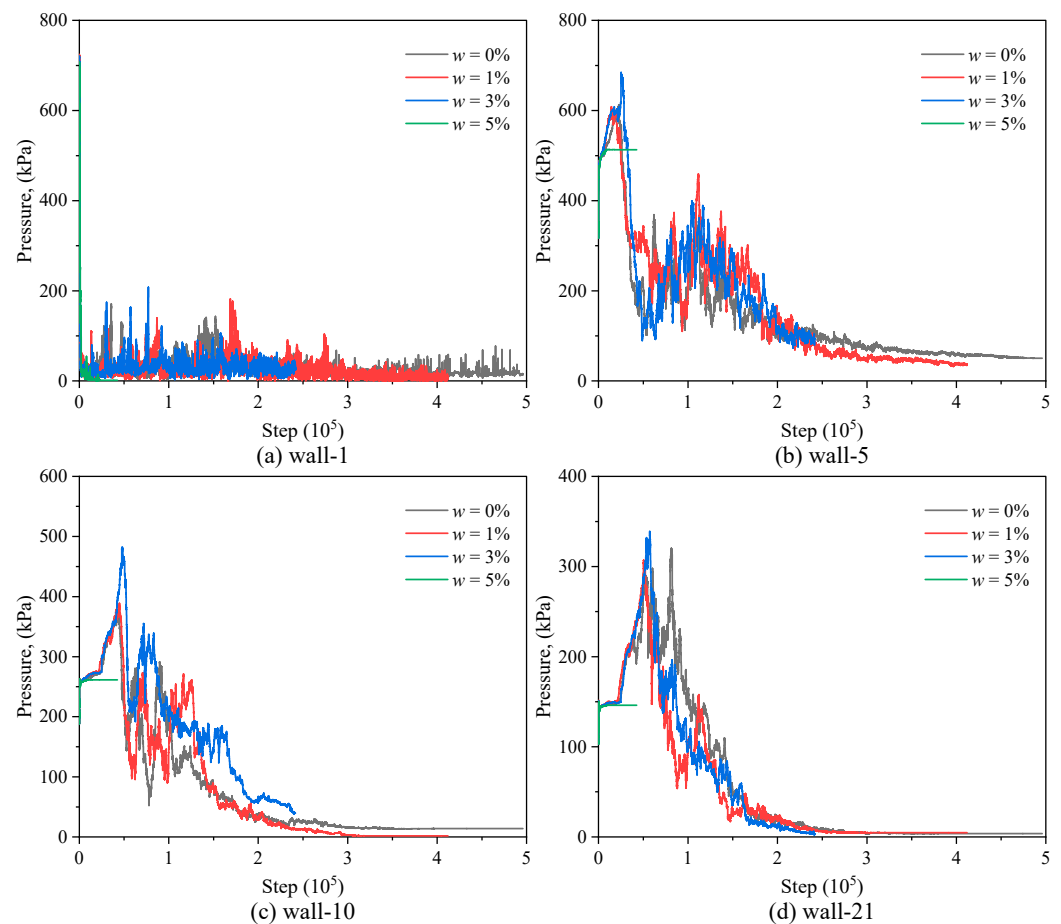


Figure 22. Dynamic wall pressure changes during the discharge process at different moisture contents.

The study indicates that at lower moisture content, the coal flow in the bunker exhibits mass flow with lower wall pressure, resulting in less adhesive clogging. As moisture content increases, coal adhesion strengthens, the flow pattern shifts from mass flow to funnel flow, and bunker wall pressure rises, leading to coal adhesion and agglomeration, and consequently, adhesive clogging. Therefore, the raw coal moisture content is a critical factor in adhesive clogging issues in coal bunkers. By controlling the moisture content to improve coal flow, the risk of adhesive clogging can be effectively reduced.

3.3.3. Influence of Coal Storage Height on Adhesive Clogging of Coal Bunker

(1) Coal flow characteristics

In this study, under the conditions of a hopper angle $\alpha = 60^\circ$ and a raw coal moisture content $w = 3\%$, we set coal storage heights h at 3 m, 5 m, 7 m, 10 m, and 20 m, with the numerical calculation model depicted in Figure 23.

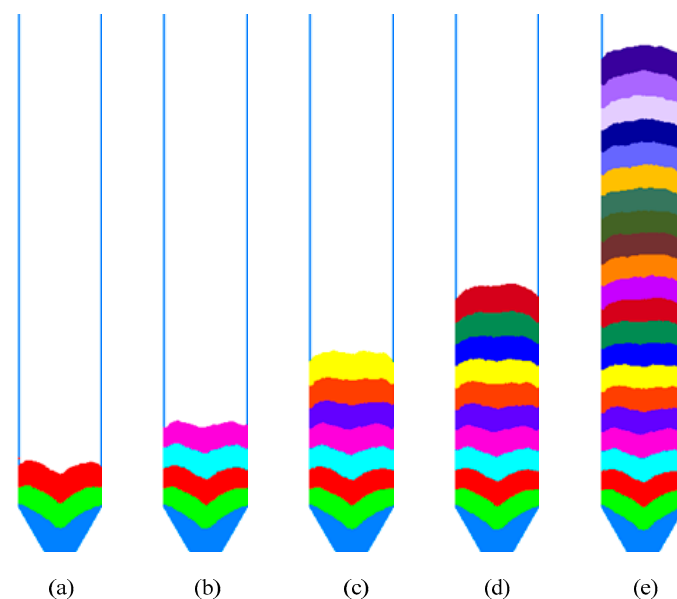


Figure 23. Numerical calculation model of coal bunker with different coal storage heights: (a) $h = 3$ m; (b) $h = 5$ m; (c) $h = 7$ m; (d) $h = 10$ m; (e) $h = 20$ m.

Simulation calculations provided insights into the distribution of coal discharge flow velocities at varying storage heights, as shown in Figure 24. At $h = 3$ m, the coal flow velocity within the bunker is relatively high, exhibiting characteristics of mass flow. Conversely, at $h = 5$ m and 7 m, the flow velocity decreases significantly, transitioning to funnel flow. At $h = 10$ m and beyond, the coal movement is negligible, leading to arching and blockage. It is evident that as storage height increases, the compaction force and adhesive interactions between coal particles intensify, affecting flow velocity and altering the flow state, which in turn increases the occurrence of adhesive coal and, in severe cases, results in arching blockages.

(2) Adhesive clogging situation of coal bunker

Figure 25 shows the adhesive blockage conditions in coal bunkers at various storage heights. At $h = 3$ m, the distribution of adhesive coal aligns with the storage sequence, and coal discharges in an orderly mass flow state. At $h = 5$ m and 7 m, adhesive coal forms layered mixed deposits, consistent with a “last-in, first-out” pattern. Thus, the storage height influences the flow state of coal, affecting the distribution of adhesive blockages within the bunker.

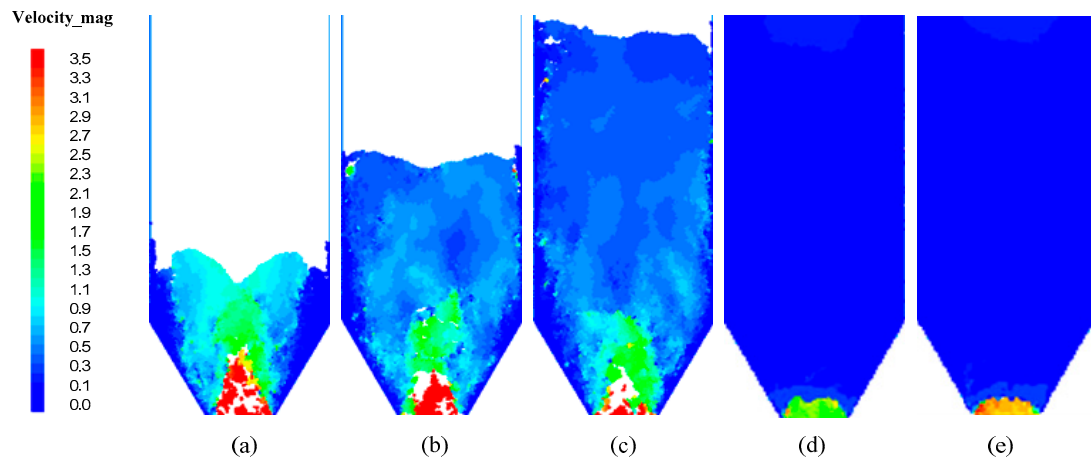


Figure 24. Coal flow velocity distribution under different coal storage height conditions: (a) $h = 3$ m; (b) $h = 5$ m; (c) $h = 7$ m; (d) $h = 10$ m; (e) $h = 20$ m.

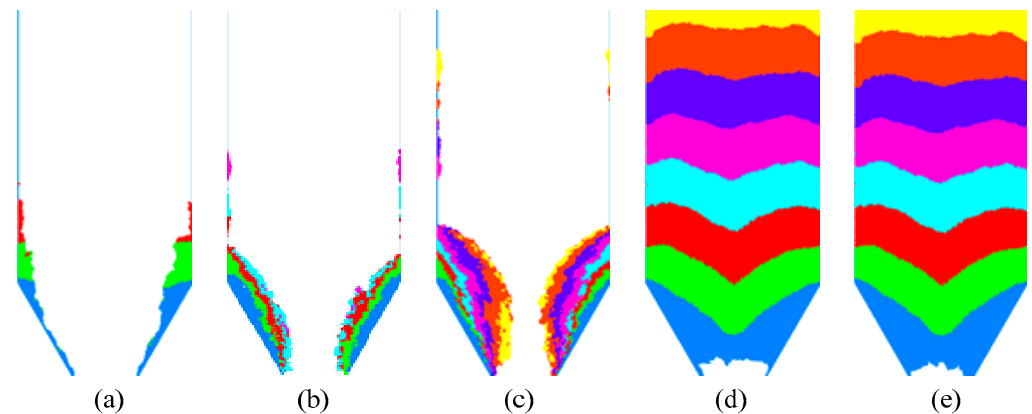


Figure 25. Adhesive clogging situation of coal bunker under different coal storage height conditions: (a) $h = 3$ m; (b) $h = 5$ m; (c) $h = 7$ m; (d) $h = 10$ m; (e) $h = 20$ m.

Figure 26 presents the variation curve of the adhesive coal mass fraction with storage height. It indicates that at $h = 3$ m, 5 m, and 7 m, the bunker experiences varying degrees of adhesive coal, with mass fractions of 9.78%, 16.97%, and 28.14%, respectively. At $h = 10$ m and 20 m, arching blockages occur, with mass fractions reaching 90.36% and 98.18%, respectively, severely affecting the bunker's functionality.

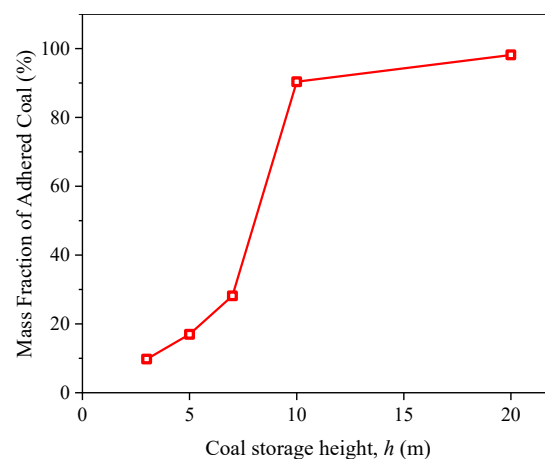


Figure 26. Curve of mass fraction of adhered coal in coal bunker as a function of coal storage height.

(3) Pressure distribution on the coal bunker wall

Given that severe arching blockages occur at $h \geq 10$ m, resulting in minimal changes in wall pressure, this study focuses on bunkers with storage heights of 3 m, 5 m, and 7 m. Dynamic pressure changes on the walls during discharge are shown in Figure 27. As h increases, the initial static pressure on the bunker wall increases significantly, the compaction force on the coal increases, the contact force between the coal particles increases, and the adhesion effect is enhanced. Simultaneously, the peak dynamic wall pressure during the discharge process increases significantly, prompting the coal to adhere to the bunker wall more frequently and thus exacerbating the coal adhesion.

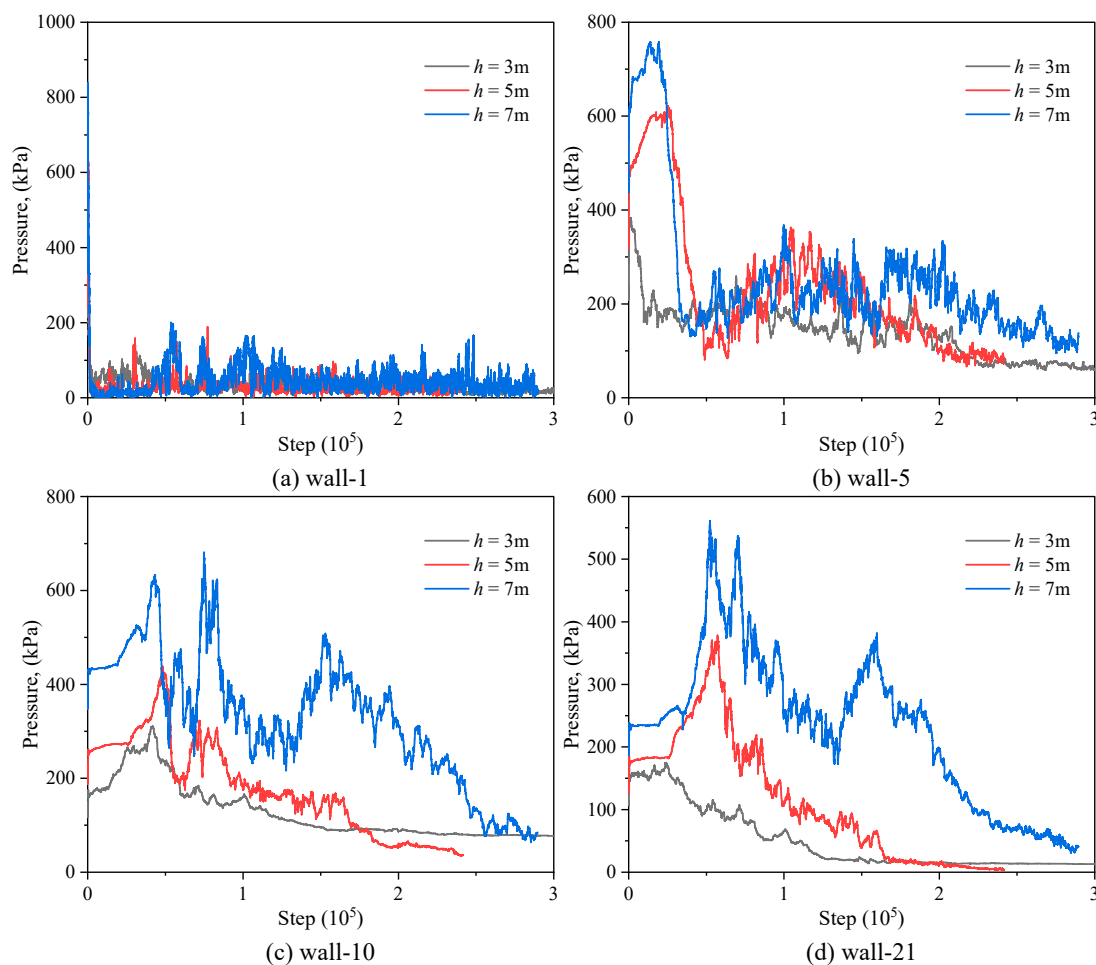


Figure 27. Dynamic wall pressure changes during the discharge process at different coal storage heights.

In conclusion, the coal storage height in bunkers affects the degree of coal compaction and flow state, leading to adhesive blockages. Scientific planning of storage height can reduce contact forces between coal particles or between coal and bunker walls, lowering the likelihood of blockages and ensuring efficient operation of underground coal bunkers.

4. Discussion

4.1. Discussion on Influencing Factors of Adhesion Properties of Raw Coal

This section systematically examines the effects of moisture content and compaction force on the adhesion properties of raw coal. By integrating existing research findings, the intrinsic mechanisms of interfacial property changes between particles are analyzed in detail. The results demonstrate that increasing moisture content significantly enhances

the cohesion at both the coal-coal and coal-wall interfaces. This phenomenon is primarily attributed to the formation of liquid bridges and negative pressure effects by adsorbed water between coal particles, thereby strengthening the adhesive force between particles. These findings align with the conclusions of Samadani [12], Jiao [13,14], and Younes [15], who identified liquid bridge forces generated by adsorbed water at particle interfaces as the primary drivers of particle agglomeration. The variation in internal friction angles further underscores the significant role of moisture content. At lower moisture levels, the internal friction angle increases rapidly, but as the moisture content rises further, the growth rate diminishes. This trend is consistent with the findings of Prokes [34] and Dahri [35], which indicate that adsorbed water enhances friction between particles at low moisture levels, while lubrication effects become dominant at higher moisture levels. Moreover, under identical moisture conditions, the cohesion and internal friction angle at the coal-wall interface consistently exceed those at the coal-coal interface. This can be attributed to the smoother and more uniform surface of the bunker wall, which allows for more substantial interfacial contact. This also explains why raw coal is more prone to adhering to the bunker wall. Unlike previous studies that primarily focused on particle-particle interfaces, this research provides new data insights into the characteristics of the coal-wall interface, offering a deeper understanding of coal bunker adhesion issues.

Additionally, increasing compaction force also enhances the cohesion at both interfaces. The results indicate that higher compaction forces intensify the mechanical interlocking of particles at the interfaces, consistent with the findings of Ku et al. [36] on the effects of particle compression. However, this study further reveals that beyond a certain threshold of compaction force, the cohesion at the coal-wall interface approaches saturation. This is because the degree of interfacial contact under high-pressure conditions approaches its limit, resulting in a diminished increase in mechanical interlocking. In contrast, the coal-coal interface, with its larger interstitial voids, exhibits a more pronounced increase in cohesion with rising compaction force. This suggests that reducing the friction coefficient of the bunker wall could be an effective strategy to mitigate coal adhesion. Regarding the internal friction angle, compaction force significantly elevates its values at both interfaces, with the coal-wall interface consistently exhibiting higher internal friction angles than the coal-coal interface. Under high-pressure conditions, tighter particle contacts amplify frictional effects, further increasing the internal friction angle.

By comprehensively analyzing the mechanisms of moisture content and compaction force, this study reveals the differences in adhesion properties between coal-coal and coal-wall interfaces and their influencing factors. These findings not only align with previous research on liquid bridge and frictional force mechanisms but also expand the scope of analysis to include the coal-wall interface. This extension provides novel insights for addressing adhesion issues in coal bunkers.

4.2. Discussion on Influencing Factors of Adhesive Clogging in Underground Coal Bunkers

This section systematically discusses the effects of coal bunker convergence angle (α), raw coal moisture content (w), and coal storage height (h) on the adhesive clogging characteristics of underground coal bunkers. The results demonstrate that the convergence angle (α) significantly affects coal flow patterns, the degree of adhesive clogging, and pressure distribution on the bunker walls. As α increases, coal flow velocity improves significantly, with the flow pattern transitioning from central flow to mass flow. This finding aligns with Ding et al. [25], who reported the relationship between flow patterns and the geometric characteristics of bunker outlets. At lower angles (e.g., $\alpha = 50^\circ$), coal exhibits central flow characteristics with slow velocities and significant retention near the bunker walls. In contrast, at $\alpha = 70^\circ$, coal achieves mass flow, with minimal retention and a

marked reduction in adhesive clogging. However, excessively high angles result in overly rapid coal discharge, complicating process control. Moreover, changes in α significantly influence wall pressure distribution. As α increases, wall pressure decreases, indicating reduced contact force between coal and the bunker wall, thereby mitigating adhesion. Unlike prior studies, which primarily focus on static pressure distributions [37–39], this study incorporates dynamic discharge analysis, revealing the impact of angle variation on pressure fluctuations. Based on operational efficiency and discharge safety, an angle of $\alpha = 60^\circ$ is recommended as it effectively reduces adhesive clogging risk while maintaining flow stability.

Raw coal moisture content (w) also significantly impacts adhesive clogging behavior. Under low moisture content (e.g., $w = 0\%$), coal exhibits good overall flowability, characterized by mass flow. As w increases, adhesion intensifies, transitioning the flow pattern to central flow. This trend is consistent with Dai et al. [16,40], who highlighted the effect of liquid bridge forces on particle flowability. The proportion of adhesive coal increases markedly with w . At $w = 3\%$, significant coal agglomeration emerges, substantially elevating clogging risk. At $w = 5\%$, coal loses flowability entirely. Higher moisture content enhances inter-particle aggregation. Wall pressure peaks increase significantly under high-moisture conditions, reflecting stronger adhesion to the walls, exacerbating clogging. By systematically simulating wet coal behavior, this study elucidates the mechanisms underlying adhesion and flow failure, providing quantitative guidance for controlling raw coal moisture levels.

Coal storage height (h) critically influences adhesive clogging as it directly impacts compaction forces and flow distribution. The findings indicate that as h increases, the flow pattern transitions from mass flow to central flow, with a significant velocity reduction. The proportion of adhesive coal exhibits nonlinear growth with h . At $h \leq 7$ m, adhesive coal distribution aligns with the flow pattern. At $h \geq 10$ m, the proportion exceeds 90%, indicating severe clogging. Furthermore, higher storage heights increase static wall pressure, intensify inter-particle contact forces, and amplify adhesion, consistent with the findings of Janoszek et al. [41] regarding the relationship between compaction forces and adhesive behavior. This study quantifies adhesive clogging under varying storage heights using numerical simulations, providing refined insights into bunker behavior.

The analysis of coal bunker convergence angle, raw coal moisture content, and storage height reveals that coal flow patterns and adhesion characteristics are governed by the coupling effects of these factors. Through numerical simulation, this study identifies the critical conditions and mechanisms of these influencing factors. In practical engineering applications, optimizing the convergence angle (recommended $\alpha = 60^\circ$), controlling raw coal moisture content (preferably not exceeding 3%), and scientifically planning storage height (preferably not exceeding 7 m) can significantly improve coal flowability and reduce clogging risks. This research provides valuable references for the design and operation of coal bunkers. Future studies will further integrate complex working conditions and multi-physics coupling models to optimize design parameters and enhance the operational efficiency and safety of underground coal bunkers.

5. Conclusions

In this study, based on the Jenike shear test principle, we designed a raw coal shear test system and utilized it to conduct tests on coal under different conditions, obtaining the variation patterns of raw coal adhesion properties. Employing the obtained parameters and the PFC2D software, we simulated and analyzed the coal flow characteristics, bunker wall pressure changes, and adhesive clogging characteristics during the discharge process of coal bunkers under different conditions, and the following main conclusions were drawn:

- (1) The raw coal adhesion properties under different moisture contents, compaction forces, and shear interface conditions were obtained using the raw coal shear test. The results demonstrate that as the moisture content and compaction force of raw coal increase, the cohesion and internal friction angle at both the coal-coal and coal-wall interfaces exhibit an increasing trend. After the raw coal moisture content reaches 3%, its influence on the internal friction angle of the two interfaces diminishes. Beyond a moisture content of 3%, the internal friction angle was less affected by moisture. Beyond a compaction force of 400 kPa, the cohesion and internal friction angle at the coal-wall interface decreased. At the same moisture and compaction conditions, the coal-wall interface adhesion parameters exceeded those at the coal-coal interface, indicating a higher tendency for coal particles to adhere to bunker walls.
- (2) During bunker discharge, when $\alpha < 60^\circ$, the coal particles inside the coal bunker exhibit central flow characteristics, with high wall pressure and significant residual adhesive coal after discharge. When $\alpha > 60^\circ$, the adhesive coal inside the coal bunker is further reduced, but the coal flow rate during discharge is relatively high, making related control difficult. At $\alpha = 60^\circ$, the adhesive coal is significantly reduced, the coal flow rate inside the bunker is stable, and the wall pressure is moderate, making this value more suitable for underground coal bunkers.
- (3) When the moisture content w is relatively low, the coal material exhibits good flowability. As w increases, the adhesion properties of the coal material gradually strengthen, and the proportion of adhesive coal inside the bunker significantly increases. After w reaches 3%, the amount of adhesive coal in the coal bunker increases more than threefold compared to lower w values, the coal flow pattern transitions from mass flow to central flow, and the wall pressure increases. When w further increases, severe arching blockage occurs inside the coal bunker. Hence, controlling the moisture content of the coal material can improve its flowability and effectively reduce the risk of adhesive clogging.
- (4) As bunker storage height h increased, compaction force and adhesion strength of coal material rose, decreasing flow rate, increasing dynamic wall pressure peaks, and significantly raising the mass proportion of adhesive coal. When h exceeds 7 m, the coal bunker is highly prone to arched clogging. Hence, a more scientific and reasonable coal storage height planning can help reduce the contact forces between coal particles or between coal particles and the bunker wall, thereby decreasing the probability of adhesive clogging.

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Conflicts of Interest: The authors declare no competing interests.

Abbreviations

A _{ad}	Ash content on air-dried basis
FC _{ad}	Fixed carbon on air-dried basis
M _{ad}	Moisture on air-dried basis
S _{td}	Sulfur total on dry basis
V _{daf}	Volatile matter on dry, ash-free basis

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