Experimental Investigation on the Grading Optimization and Storage Effect of Crushed Gangue for Backfill

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Abstract

Coal mine backfilling mining controls the movement of overlying rock and surface subsidence by backfilling the fractured rock mass into the goaf. The compaction mechanical performance of the fractured rock is the key to the effectiveness of overlying rock control. In order to optimize the control effect of crushed gangue overlying rock, this article focuses on the regulating effect of gangue particle size grading on mechanical properties. Through research on the physical properties of gangue and natural graded gangue compaction experiments, the porosity of gangue crushing and the process of gangue crushing are analyzed. It is shown that the gangue material has good load-bearing performance in terms of physical structure, and the elastic modulus has an absolute effect on the compression characteristics of gangue particles. Through storage analysis of the natural grading experiment phenomenon, it was found that the alarm height for gangue not to be blocked is 20m. Through laboratory experiments, the compression characteristics of group B samples were analyzed, and it was found that the particles showed a trend of first increasing and then decreasing under the coupling effect of particle size and particles of different sizes. Through the analysis of particle strain energy density and breakage energy, it is concluded that the strain energy density of the sample from high to low is B1, B2, B6, A5, B5, B4, and the breakage energy consumed to reach the sample broken state from low to high is A5, B6, B5, B4, B3, B2, B1, so the B6 group samples have the best economic benefits. Through analysis from the perspective of filling rate, it was found that the B6 group of samples has the best control effect on the overlying rock. Thus providing suggestions for optimizing the efficiency and effectiveness of backfill mining.

1. Introduction

Coal gangue is a solid waste associated with the production process of coal mines, and each ton of coal can be accompanied by 0.15 to 0.2 tons of coal gangue. The coal mining face and excavation working face are the main production areas of gangue. Gangue blocks are stored on the surface in a natural accumulation form. Gangue contains a certain amount of organic matter and heavy metals, which not only poses a safety hazard of explosion induced by oxidative heat release, but also poses a problem of soil heavy metal pollution caused by water leaching.

In order to reduce mining waste pollution and disasters, and prevent surface subsidence induced by mining activities, coal mine technicians have proposed a green coal mining technology based on coal waste filling[1–4]. In the underground space (goaf) formed by underground coal mining, a certain degree of fragmentation (< 50 mm) of coal gangue is backfilled to form a spatial structure of "overlying rock - gangue body - bottom rock" goaf, which alleviates the collapse and subsidence movement of overlying rock caused by the loss of coal seam support[5–8]. The gangue filling body is in full contact with the overlying rock layer, generating resistance to the subsidence and fracture of the overlying rock, and playing a key bearing role in the spatial structure of the goaf[9–11]. Some scholars have theoretically analyzed the optimization design of filling effect and qualitatively analyzed the main controlling factors of filling effect[12–14]. Some scholars have introduced a nonlinear Winkler foundation model to explore
the control factors of gangue filling on the overlying rock structure, and summarized four key factors: gangue lithology, particle size grading, initial compaction strength, and initial compaction frequency[15].

The key to the analysis of spatial structural stability of "overlying rock - gangue body - bottom rock" is to clarify the mechanical deformation behavior characteristics of gangue backfill under the action of overburden subsidence. The gangue filling body is a non continuous medium with complex lithology and has typical properties of particle size grading of loose materials. The lithology and particle size distribution directly affect the load-bearing deformation behavior of the filling material[16, 17]. Domestic and foreign scholars have conducted a series of studies on the bearing mechanical behavior of fractured rock masses. Scholars have studied the compaction characteristics of collapsed rock masses in goaf areas, focusing on analyzing the relationship between tangent and secant moduli and stress during the compaction process of rock blocks[18, 19]. Scholars have conducted a series of limestone particle compaction experiments, focusing on the impact characteristics of particle size distribution factors on compaction characteristics[20–23]. Some scholars have studied the long-term creep mechanical behavior of gangue filling materials on self-developed bidirectional compaction experimental equipment[24–26]. Scholars have proposed a characterization method for fractal characteristics used to describe the compaction process of gangue[27–29].

Existing research mostly focuses on optimizing the filling process and compacting behavior of gangue, with less attention paid to the practical difficulties exposed by on-site engineering. For example, the blockage behavior caused by the self weight of the gangue in the gangue storage warehouse, as well as the complexity of the lithology, make it difficult to strictly control the degree of gangue fragmentation[30–32]. The amount of gangue associated with coal mining often cannot meet the filling demand of goaf. In actual production, gangue needs to be transported in reverse from coal preparation plants and power plants, and long-term transportation can lead to uneven particle size distribution. Especially during the vertical delivery of gangue from the ground to deep engineering sites through vertical shafts, the high-speed falling of gangue also significantly affects the particle size distribution characteristics of the gangue.

This article conducts a series of compaction mechanical tests on gangue, analyzing the compaction mechanical behavior of naturally graded gangue and artificially controlled graded gangue. By analyzing and clarifying the evolution characteristics of the apparent mechanical properties of gangue powder during the compaction process. By exploring the filling rate of goaf and optimizing the blockage prevention of storage bins, theoretical guidance and technical support are provided for on-site engineering practice.

2. Methodology

2.1 Sample preparation
The test samples are from the 10 million ton scale Hulusu coal mine in western Ordos, Inner Mongolia, China. Some of them were taken from the gangue accumulation site and some were taken from the washing gangue of the coal preparation plant. The lithology of gangue is mainly sandstone, mainly composed of coal seam roof and floor rocks that have been cut and broken during coal mining. The original sample of gangue has a significant difference in particle size, mainly consisting of large-sized blocks. After natural accumulation, there is a large pore space between the particles, resulting in poor overall stability and easy compression deformation. The original gangue sample usually requires secondary crushing to obtain a suitable particle size for filling (< 50 mm). The laboratory prepared crushing test sample is shown in Fig. 1.

The experimental samples are divided into three groups as a whole. One group is used for measuring physical parameters such as density, porosity, pore structure, and bulk density. The second group is used to analyze the compaction deformation behavior, and the third group is used for preparing different graded gangue aggregates through three rounds of crushing. The overall experimental overview is shown in Fig. 2.

### 2.2 Determination of the physical properties

The natural stacking density, particle density, and particle size distribution are key physical indicators of gangue filling materials. The measurement of natural stacking density and particle density is closely related to pore structure. The pore structure of loose materials (soil, crushed stone, gravel, etc.) includes inter particle pores, inter particle interconnected pores, and inter particle closed pores, with significant multi-scale characteristics. The calculation volume of the natural packing density of loose particles is generally defined as the sum of the skeleton of loose particles, intergranular pores, through pores, and closed pores. The density of loose particles is the sum of the skeleton of loose particles, through pores, and closed pores.

Before and after crushing the gangue, the density of the gangue particles is measured using a balance and a measuring cylinder. This measurement method adopts the underwater weighing method in the standard GB/T 23561 "Methods for determining the physical and mechanical properties of coal and rock". When measuring the breakage density of the crushed gangue body, plastic film is used to wrap the test material. In order to truly reflect the natural stacking state, the film is fully vibrated to shrink the space and make full contact between the gangue particles. A total of 10 samples were set up for measurement and analysis in the experiment.

The pore structure characteristics of broken gangue particles were characterized using nuclear magnetic resonance testing. The experimental instrument was the MacroMR12-150H-I low-temperature and high-pressure nuclear magnetic resonance instrument from the School of Mines, China University of Mining and Technology. The magnet temperature was 32 ± 0.01 °C, the main magnetic field strength was 0.3 ± 0.05 T, the magnet frequency was 10.64–14.90 MHz, the magnet uniformity was ≤ 50 ppm (150 mm sphere), the magnet stability was ≤ 300 Hz/Hour, the frequency source range was 1–30 MHz, and the
pulse control accuracy was 0.1 Hz, Pulse accuracy of 100 ns. Before the experimental measurement, the gangue was soaked for 120 hours for saturation, and the porosity and pore size distribution of the gangue were determined based on the distribution of nuclear magnetic resonance T2 peak signal. A total of 10 samples were set up for measurement and analysis in the experiment.

2.3 Compression tests

The compaction characteristics of gangue were measured on the MTS816 mechanical testing machine. During the experiment, the gangue samples were placed in a self-developed bulk material compaction test tube to simulate the lateral constraints on the gangue in the engineering site. The loading shaft of the testing machine is loaded through the experimental cylinder matched with a piston, simulating the load (self weight, mining pressure, fluid pressure, etc.) on the gangue at the engineering site. The experimental cylinder and piston are made of 45 # steel, with an elastic modulus of 210 GPa and a Poisson's ratio of 0.35; The inner diameter of the experimental cylinder is 100 mm, the outer diameter is 114 mm, and the cylinder height is 200 mm; The piston has a diameter of 99 mm and a height of 10 mm. During the experiment, sensors are used to collect parameters such as axial stress, strain, and displacement. During the experiment, the testing machine was loaded using stress control and pressurized at a constant rate of 0.5 kN/s. The loading path and sample type of the entire group of experiments are divided into three scenarios, and the specific experimental parameter settings are shown in Table 1.

(a) Natural graded broken gangue, with different experimental groups set different maximum loading pressures.

(b) Different grading broken gangue, with a maximum loading pressure of 16 kN, and different experimental groups set different grading characteristics:
Table 1
The detailed parameters of three test schemes

<table>
<thead>
<tr>
<th>Group</th>
<th>Loading Force</th>
<th>Grains Size Gradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Variable-Loading Force</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>4 kN</td>
<td>Natural Gradation</td>
</tr>
<tr>
<td>A2</td>
<td>4.5 kN</td>
<td>0–5 mm, 13.56%;</td>
</tr>
<tr>
<td>A3</td>
<td>5 kN</td>
<td>5–10 mm, 13.03%;</td>
</tr>
<tr>
<td>A4</td>
<td>6 kN</td>
<td>10-20mm, 12.10%;</td>
</tr>
<tr>
<td>A5</td>
<td>16 kN</td>
<td>20–30 mm, 20.60%;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30–40 mm, 19.67%;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40–50 mm, 21.04%;</td>
</tr>
<tr>
<td>B</td>
<td>Variable-Gradation</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>16 kN</td>
<td>0–5 mm</td>
</tr>
<tr>
<td>B2</td>
<td>50%</td>
<td>5–10 mm</td>
</tr>
<tr>
<td>B3</td>
<td>33.33%</td>
<td>10-20mm</td>
</tr>
<tr>
<td>B4</td>
<td>25%</td>
<td>20-30mm</td>
</tr>
<tr>
<td>B5</td>
<td>20%</td>
<td>30-40mm</td>
</tr>
<tr>
<td>B6</td>
<td>16.67%</td>
<td>40-50mm</td>
</tr>
</tbody>
</table>

3. Results and analysis

3.1 Physical properties of coal gangue in study area

Before and after the fragmentation of the gangue, the density of the gangue particles (d > 100 mm) and the gangue fragments were measured using an electronic balance and a measuring cylinder. The 10 sets of measurement results showed that the density of the gangue particles before fragmentation was about 2.513 t/m3, and the density of the gangue fragments was 1.265 ~ 1.462 t/m3, with an average of 1.364 t/m3. This indicates that the internal porosity of the gangue after fragmentation has significantly increased, forming a considerable pore space in the gangue fragments. The inter particle pores formed by crushing are the main deformation objects of gangue during the loading process. Generally, the fracture expansion coefficient k0 is used to evaluate the ability of rock mass to form pore space due to fragmentation, and the effective porosity ne is used to evaluate the compactability of fractured rock masses. The calculation method for the coefficient of fragmentation and effective porosity of rocks of
the same quality is shown in Eq. (1). The average coefficient of fragmentation and effective porosity of gangue secondary crushing (<50 mm) can be calculated as 1.816, and the average effective porosity is 0.454. In subsequent compaction characteristics experiments, this value is used as the initial value to analyze the evolution of gangue compaction characteristics through the variation characteristics of two indicators.

\[
\begin{align*}
  k_0 &= \frac{V_1}{V_0} = \frac{\rho_0}{\rho_1} \\
  n_e &= \frac{V_m}{V_0} = 1 - \frac{1}{k_0}
\end{align*}
\]

Where \(V_1\) is the initial volume of the rock mass, \(m^3\); \(V_0\) is the volume of rock mass after fragmentation, \(m^3\); \(\rho_0\) is the initial density of the rock mass, \(t/m^3\); \(V_m\) is the volume of intergranular pores in the crushed gangue, \(m^3\).

The microporous structure of gangue particles is an important indicator for evaluating the compaction bearing strength of gangue. To evaluate the later bearing characteristics of coal gangue from Hulusu Coal Mine, 10 suitable particle size gangue particles were selected for nuclear magnetic resonance testing. The measurement results are shown in Table 2. After secondary crushing, the porosity of gangue is between 7% and 11%, the minimum porosity is 7.12%, the maximum porosity is 10.595%, and the average porosity is 8.58%, with relatively high compactness. The pore size inside the gangue is almost always below 10 µm, with pore sizes below 0.1 µm accounting for more than half of the total pore volume. The pore radii of No. 5 and No. 7 gangue samples are less than 0.1 µm, accounting for 57% and 54% of the total pore volume. Other gangue samples have pore radii less than 0.1 µm, accounting for more than 80% of the total pore volume. The pore radius of the No.9 gangue samples is less than 0.1 µm, accounting for more than 93% of the total pore volume. They have good load-bearing performance in terms of physical structure.

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-porosity</td>
<td>7.842</td>
<td>8.471</td>
<td>8.780</td>
<td>8.460</td>
<td>9.917</td>
</tr>
<tr>
<td>Sample</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Micro-porosity</td>
<td>7.488</td>
<td>10.595</td>
<td>9.368</td>
<td>7.120</td>
<td>7.786</td>
</tr>
</tbody>
</table>

3.2 Response characteristic of gangue with natural gradation during compaction
The compression test results of natural ratio coal gangue are shown in Fig. 4. Figure 4a shows the compaction test data of naturally graded gangue in groups A1 to A4. During the experimental process, especially during the compaction process with a load of 5 kN, the stress-strain curve exhibited strong fluctuations. But overall, the relationship between stress and strain is basically linear. After the experiment, it was found that when dumping the gangue, the steel cylinder was unable to pour out the gangue under loads of 5 kN and 6 kN, and auxiliary means were needed for crushing. When the load was 4 kN, the gangue could be completely poured out, and there was local blockage at a load of 4.5 kN. In Fig. 4a, it is shown that the degree of gangue fragmentation is more severe under a load of 5 kN compared to a load of 6 kN, this indicates that a significant fragmentation behavior occurred at a load of 5 kN. Therefore, at a load of 5 kN, the compaction deformation is the largest, and the stress-strain curve fluctuates the most severely.

Figure 4b shows the compressive stress-strain curve of naturally graded gangue in Group A5. The average deformation is about 0.415 under a force of 16 MPa. The stress-strain relationship exhibits a distinct two-stage characteristic, with rapid growth in the early stage and gradual flattening in the later stage. This trend can be well described using a logarithmic function. Although the six samples come from the same batch of gangue raw materials, there are still significant differences in compaction deformation and elastic modulus. After the experiment, the gangue inside the steel cylinder is completely compacted and cannot be poured out without the help of auxiliary means. It is generally believed that the fluctuation of stress-strain curve during the compaction process of loose materials is closely related to the secondary fragmentation of particles and the adjustment of loose structure. The discreteness of the compaction deformation behavior of the six samples in Fig. 4b may be related to the strong anisotropy of the spatial structure of the gangue fragmentation.

In the study of the complete stress-strain curve of rocks, it is believed that the compression process of rocks can be divided into two stages: macroscopic pore crack compaction stage and microscopic pore crack development and failure stage. Analogous to the rock compression curve, the compaction deformation of gangue can be divided into two parts: the early stage mainly involves intergranular pore compression deformation, and the effective porosity plays an important role in characterizing it; In the later stage, the compression failure between gangue particles mainly occurs, and micro pores and cracks play an important characterization role. The significant anisotropy of the spatial structure of gangue particles is a key factor in the difference in elastic modulus between Fig. 4a and Fig. 4b. By calculating the tangent modulus, the data in the following tables are obtained. Table 3 shows the elastic modulus of the A1 ~ A4 group gangue samples, Table 4 shows the standard deviation of the modulus of the A1 ~ A5 group gangue samples, and Table 5 shows the initial and later elastic modulus of the A5 gangue samples. From the standard deviation in the table, it can be seen that as the gangue crushing body gradually compacts, the tangential elastic modulus gradually approaches, reflecting the gradual stability of the spatial structure of the gangue crushing body, and the elastic modulus is gradually determined by the compression characteristics of the gangue particles.
3.3 Response characteristic of gangue with manual gradation during compaction

In on-site engineering practice, under the influence of external environment, the crushed gangue often loses its natural grading characteristics, and different particle sizes of coal gangue are disorderly mixed together. The particle size grading significantly affects the compaction mechanical properties of coal gangue. The disordered characteristics of on-site gangue fragmentation will lead to unstable filling effect in the goaf, making it difficult to effectively determine process parameters. Therefore, proportioning according to a certain proportion to obtain fixed grading characteristics of gangue filling has gradually become an important development trend. The Test B experimental plan focuses on six intervals: 0–5 mm, 5–10 mm, 10–20 mm, 20–30 mm, 30–40 mm, and 40–50 mm. From small to large, B1 to B6 groups of experimental samples were prepared. The specific grading characteristics are shown in Table 6.

The stress-strain curves of B1 ~ B6 gangue compression tests are plotted in Fig. 5a. The six sets of compaction curves can be described using logarithmic functions and all have good fit. In Fig. 5b, the initial elastic modulus and final deformation variables of six sets of experiments are organized, and the corresponding average values of natural graded gangue compaction of A5 group samples are identified in the figure. From Fig. 5, it can be seen that the elastic modulus of experimental groups B1 to B6 showed a monotonic increase trend, and the final deformation variable showed a trend of first increasing and then decreasing. The initial loading rate control error of B3 group resulted in a higher elastic modulus, while rapid loading may cause some gangue to compress and break instantly, resulting in a smaller final deformation recorded in the experiment. The shaded part of the column chart in Fig. 5b shows the estimated values of the modulus and deformation of the B3 group gangue, which will be discussed and analyzed in the following text. To determine the optimization effect of grading characteristics on gangue
fragmentation, the average initial elastic modulus and average final deformation variable of A5 natural grading group are added in Fig. 5b. The data comparison shows that the initial elastic modulus of B1 ~ B5 groups is lower than that of natural grading group A5, while the initial elastic modulus of B6 group is slightly higher than that of A5; The total compression deformation of B4 is higher than that of the natural grading group A5, while other groups are all lower than A5.

The initial elastic modulus and final deformation variable can reflect the spatial contact structure and particle size distribution characteristics of the gangue crushing body. As shown in Table 6, the proportion of particles with sizes ranging from 40 to 50 mm in the A5 group reached 21.04%, while in the Test B sample group, only B6 contained particles with sizes ranging from 40 to 50 mm. The load-bearing structure formed by staggered movement between particles is the main mechanical behavior in the early stage of compaction. The larger the particle size of gangue, the higher the proportion of larger particle size gangue, which is more conducive to the stability of the load-bearing structure. The lack of gangue with a large particle size of 40–50 mm may be an important reason for the low early elastic modulus of B1 ~ B5 groups. Related studies have shown that the compacted and crushed gangue tends to have a stable grading structure, with a particle size distribution mainly ranging from 0 to 10 mm. B1 and B2 are mainly composed of gangue with a particle size of 0–10 mm, so the final deformation is relatively small. The compaction deformation variables of B3 ~ B6 groups first increase and then decrease. It is generally believed that the compression deformation of large particle size gangue is the key to effective load-bearing structure, while the staggered filling of small particle size gangue can effectively supplement the load-bearing structure. As the particle size gradually increases, on the one hand, large particles break and deform, and on the other hand, particles with different particle sizes cooperate to resist deformation. Under the coupling of the two effects, there is a trend of initially increasing and then decreasing.

### Table 6
The characteristics of Grain Size Distribution in Test B1 ~ B5 and Test A5

<table>
<thead>
<tr>
<th>Test</th>
<th>Maximum particle (mm)</th>
<th>Percent finer (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0 ~ 5</td>
<td>100</td>
</tr>
<tr>
<td>B2</td>
<td>5 ~ 10</td>
<td>50</td>
</tr>
<tr>
<td>B3</td>
<td>10 ~ 20</td>
<td>33.33</td>
</tr>
<tr>
<td>B4</td>
<td>20 ~ 30</td>
<td>25</td>
</tr>
<tr>
<td>B5</td>
<td>30 ~ 40</td>
<td>20</td>
</tr>
<tr>
<td>B6</td>
<td>40 ~ 50</td>
<td>16.67</td>
</tr>
<tr>
<td>A5</td>
<td>40 ~ 50</td>
<td>21.04</td>
</tr>
</tbody>
</table>

### 3.4 The energy characteristics of gangue during compaction
The energy evolution characteristics during the compression process of gangue are important evaluation indicators for backfilling mining technology[33]. In general, during the stable deformation process of on-site engineering filling gangue, it is possible to absorb sufficient external energy through sufficiently small deformation. This allows the load on the overlying rock in the mining area to be transferred to the filling gangue, avoiding strong deformation and failure of the overlying rock structure. Based on the stress-strain curves of test A5 and test B group gangue, the strain energy density curves of gangue with different particle size gradations calculated based on formula (2) are drawn in Fig. 6a.

\[ W = \int_0^\varepsilon \sigma d\varepsilon \]

Where, \( W \) is the strain energy density, MJ/m^3; \( \sigma \) is the stress, MPa; \( \varepsilon \) is the strain.

As shown in Fig. 6a, the strain energy density curve of crushed gangue has a significant three-stage feature. With the increase of gangue strain, the strain energy density increases slowly at first, then rises slowly, and finally rises sharply. Relevant literature studies also found similar laws, and pointed out that the initial inter particle pore compression, the middle particle extrusion deformation, and the later particle crushing and recombination are the essential reasons for the gradual increase of strain energy density. Horizontal comparison shows that the relative relationship between strain energy density of gangue with different particle size gradations is more complex. As shown in the partially enlarged image in Fig. 6a, before \( \varepsilon = 0.110 \), the strain energy density increases with the increase of the maximum particle diameter. Subsequently, the relative relationship underwent a transformation, with B1, B2, B6, A5, B5, and B4 ranking from high to low. The natural grading group A5 strain energy density is the highest in the early stage.

It is generally believed that the smaller the particle size of crushed gangue is, the smaller the compressible space between particles is, and the higher the energy dissipated by particle compression and crushing, so the corresponding strain energy density is larger. During this compression test, energy consumption was slow in the initial stage, and the work done by the compressive strength on the gangue was mainly used as the compression process of the void space. At this stage, the void space of gangue is closed, so the increase speed of strain energy density is small. However, before \( \varepsilon = 0.110 \), the larger the particle size, the greater the strain energy density. We do not know the specific reason for this situation. We think that the compression deformation of gangue with mixed particle size in the early stage is complex, which leads to this situation.

Figure 6b reveals an empirical model of particle accumulation. When the particles are of a single size, the broken particles show a regular and relatively close arrangement, and the strain energy density is larger at this time. When different diameter particles are added, the original regular arrangement is disrupted, and the gap between particles increases. As the difference in particle size increases, the stacking density between particles increases. Therefore, appropriately increasing particles of different particle sizes and
increasing the difference in particle size between particle components, as shown in Fig. 6b, can make the sample fragmentation close to the densest stacking. In the mid-term accelerated energy consumption stage, the work done by compressive strength is mainly used to destroy the stable structure of gangue and crush large particles, thus increasing the speed of energy consumption. In the later stage of the experiment, the compressive strength is mainly used for the closure of residual pore space and the secondary crushing of particles, so during this period, the energy dissipation of crushed gangue is significant. Group B1 samples are broken gangue particles with single size and fine particle size. The particles are arranged regularly and closely, so they have large strain energy density. The samples in group B2 and B4 are composed of 2 to 3 groups of particles with different particle sizes. With the addition of particles with different diameters, the original regular arrangement of particles is broken and the particle size difference is small, so the compactness of sample stacking is reduced and the strain energy density is reduced. The number of particle components in the B5 and B6 samples continued to increase, and the difference in particle size between the components increased, and the spatial structure between the particles was adjusted. The number of particle components in the B5 and B6 samples continued to increase, and the difference in particle size between the components increased, and the spatial structure between the particles was adjusted. This makes the finer particles fill in the cracks of closely arranged particles, and the packing density of particles increases, so the density of strain energy increases instead. Therefore, the strain energy density of sample particles in groups B1 to B6 shows a "U" trend. Group A5 is a naturally graded broken sample, and the strain energy density is lower than that of group B6. At the same time, the deformation of group B6 is appropriate, and the strain energy density is higher, so group B6 is more appropriate as a filling material.

4. Discussion

Coal mining activities form goafs, leading to surface subsidence and environmental damage. Backfilling mining is the process of backfilling the gangue pollutants generated by coal mining into the goaf, replacing the existing coal support roof with filling materials, and slowing down the movement of overlying rock layers and surface subsidence. Under the action of overlying rock load, the smaller the compressive deformation of the filling material, the stronger the control force on overlying rock movement, and can better control surface subsidence. Therefore, the control effect of backfill mining on overlying rock is closely related to the compaction mechanical properties of gangue. The particle size grading significantly affects the compaction mechanical properties of gangue, and the disorder of on-site crushed gangue can lead to unstable filling effect in goaf. Therefore, in order to improve the efficiency and stability of gangue filling, it is necessary to optimize the particle size distribution of coal gangue. The underground gangue storage bin is an important component of the backfilling mining system. The high storage height on site leads to the compaction and blockage of the gangue in the storage bin, which seriously affects the efficiency of backfilling mining. Therefore, it is very important to analyze the anti blocking system of the storage bin and determine the alarm height of the storage bin.
4.1 Analysis of the load-bearing characteristics and crushing energy of gangue with different particle size grading

When particles break, the original grading curve will also change. The grading curve can not only reflect the degree of particle fragmentation, but also serve as a basis for measuring energy dissipation during the particle fragmentation process[34]. The area enclosed by the grading curve formed during the particle crushing process is used as the crushing amount, and then divided by the defined potential crushing amount to obtain the ratio of crushing rate. The areas enclosed by the grading curves of samples with different particle sizes after testing are E1, E2, E3, E4, E5, E6, E0, respectively. The indicator of sample fragmentation is shown in Eq. (3):

\[
K_n = \frac{\sum_{j=1}^{n} E_j}{\sum_{i=0}^{6} E_i}
\]

Where: \(E_i\) and \(E_j\) are the crushing energy, and \(n\) is the corresponding sample group (groups 1 to 7 are A5, B6, B5, B4, B3, B2, B1, respectively). The fragmentation effect of each group of samples calculated is shown in Fig. 7.

By fitting the initial elastic modulus and final strain of samples in groups B1, B2, B4, B5 and B6, the corresponding elastic modulus and strain curves are obtained as shown in Fig. 7a. From this, the initial elastic modulus and final deformation of B3 group gangue samples were estimated. In Fig. 7a, it can be seen that the initial elastic modulus of each group of samples increases with the increase of the maximum particle diameter. The initial elastic modulus, from high to low, is 8.89MPa, 6.85MPa, 5.73MPa, 5.22MPa, and 4.61MPa, respectively. Therefore, the larger the particle size of gangue in the sample, the higher the proportion of large-sized gangue, which is more conducive to the stability of the load-bearing structure of the filling material. The final deformation of the gangue samples in Fig. 7a is 0.46 in B4 group, 0.41 in B5 group, 0.35 in B6 group, 0.31 in B2 group, and 0.26 in B1 group. The final deformation of the B1, B2, and B6 groups of gangue samples is relatively small, and the support effect as filling materials is better. The energy required to complete the expected limit state for 7 sets of samples is shown in Fig. 7b. When the naturally graded sample A5 needs to reach the B6 crushing state, the energy required is E1. When reaching the B5 crushing state, the energy required is the sum of E1 and E2, and the energy required is relatively small. When reaching the B2 and B1 states, the energy required is the sum of energy values in the range of E1 to E5 and the sum of energy values in the range of E1 to E6, respectively. It can be seen that when the natural particle size grading sample reaches the state of B1 and B2 components, a huge amount of energy is required. Due to the analysis in Fig. 7a, it is found that the B1,
B2, and B6 groups of gangue samples have better support effects as filling materials, while achieving the B6 group's crushing state requires the least amount of energy and has the best economic benefits. Therefore, the B6 group of samples is the most suitable filling material.

### 4.2 Analysis on the control of overlying rock movement by gangue with different particle size grading

In the process of backfilling mining, the goaf is backfilled with filling materials. The subsidence amount of the overlying rock in the goaf is limited by the height of the compacted gangue filling body. The higher the height of the compacted gangue material, the stronger the ability to control the subsidence of the roof coal and rock layers. In the process of continuously advancing the backfilling mining face, the overlying rock generally does not have periodic fractures, but it is accompanied by crack development. The degree and range of crack development are related to the height of the compacted gangue material and the lithology of the overlying rock to a certain extent. The height after compaction is defined as the filling rate. Generally speaking, the higher the filling rate, the smaller the development range of overlying rock fractures. Figure 8 is a schematic diagram of the control effect of goaf backfilling on overlying rock.

In backfilling mining, filling materials can replace the original coal body in the space to support the roof. The higher the filling rate, the better the support effect of filling materials on the roof. The filling rate refers to the ratio of the final height of the filling material in the goaf that is compacted after the settlement of the overlying rock after reaching full mining to the mining height, and the filling rate $\varphi$ is Eq. (4):

$$\varphi = \frac{h - h_d}{h}$$

Where: $h$ represents the mining height; $h_d$ is the final subsidence value of the roof; $\varphi$ is the filling rate.

It can be seen from the above compaction experiments of filling materials that the stress-strain of filling materials can fit into a good exponential form. Further solving the formula can get the expression of stress-strain as Eq. (5)

$$\varepsilon(\sigma) = a \ln(\sigma + b) + c$$

Where: $a$, $b$, and $c$ are the fitting parameters.

$$\varphi = \frac{(h - h_t)(1 - \varepsilon(\sigma) + \varepsilon(\sigma_h))}{h}$$
Where: $h_t$ represents the advanced subsidence value of the roof, and $\sigma_h$ represents the compaction strength.

When the fixed mining height is 3.2m and the advance subsidence of the roof is 0.16m, fill material samples B1, B2, B4, B5, and B6 with different particle size gradations are selected. The influence of different particle size gradations on the filling rate is calculated and shown in Fig. 9.

As shown in Fig. 9, as the burial depth of the coal seam increases, the overlying rock stress increases, the filling material is compacted, and the filling rate gradually decreases. When $\sigma$ is less than 1.78 MPa, the filling rate of B6 group gradually increases from the lowest, and the particle size difference between B6 group samples is the largest, with the largest number of different particle sizes. Thus, the B6 group samples have the property of loose accumulation in the early stage, and the anti deformation ability of the filling material is enhanced after the density increases in the later stage. The actual burial depth of the goaf is 640m, and the overburden stress is 16kN. From Fig. 9a, it can be seen that the corresponding filling rates of samples in groups B1, B2, B4, B5, B6, and A5 are 70.3%, 72.7%, 75.8%, 75.5%, 84.6%, and 76.7%, respectively. Among them, the filling rate of gangue samples with artificially controlled grading is shown in Fig. 9b. Among them, the filling rate of gangue samples with artificially controlled grading is shown in Fig. 9b, showing an overall increasing trend with the increase of the maximum particle size, while the filling rate of naturally graded samples is at a lower level. It can be seen that the main factors affecting the material filling rate are the particle size and quantity of the largest particle in the filling material. The larger the particle size of the largest particle in the sample, the greater the resistance to deformation.

### 4.3 Study on the Cementation Characteristics of Gangue Accumulation Process

The gangue storage site of Hulusu Coal Mine experiences cementation and blockage when a 28m high gangue is piled up, so it is necessary to design an anti blockage system for the storage bin. Determine and analyze the bonding characteristics of loose solid waste under constant pressure conditions through experiments, and calculate the appropriate storage height. The experimental principle is shown in Fig. 10.

$$P_a = \frac{H_1}{100} \times P_b$$

Where: $P_a$ is the upper limit of equalizing pressure; $H_1$ is the storage height; $P_b$ is the pressure increase per 100m depth, which is 2.5MPa here.

To ensure the reasonable storage of gangue in the storage bin, the MTS system is used to measure the critical load of the gangue in an unconsolidated state. The upper limit of uniform pressure is the maximum consolidation stress from the gangue in the cylinder to the coal mine storage bin. After calculation, the upper limit of the average pressure for the storage silo at a height of 28m is 5.49 kN.
Therefore, during the experiment, an average load of 4kN to 6kN was selected, and the average loads P1, P2, P3, and P4 at different heights were designed to be 6kN, 5kN, 4kN, and 4.5kN, respectively. The corresponding storage heights were 30m, 25m, 20m, and 22.5m.

When $P_1 = 6kN$, the strain changes tend to be horizontal and stabilize below 0.08 when the stress is maintained at a constant pressure stage of 0.7MPa. It indicates that when the storage bin is full and feeding is stopped, the gangue in the bin will no longer undergo significant compression deformation, and the degree of cementation will not further improve. The gangue cannot be directly poured out when it hits the metal cylinder, and is in a strong cemented state, requiring manual knocking to break and dismantle. When $P_2 = 5kN$, when the stress enters a constant pressure state, the strain changes tend to level and stabilize at 0.09. The gangue cannot be completely poured out when it hits the metal cylinder, and the lower part is in a strong cemented state, requiring manual tapping and dismantling. When $P_3 = 4kN$, after entering a constant pressure state, the strain change tends to level and stabilizes at 0.06. The gangue can be completely poured out without showing any cementation, indicating that under this load, the lower part of the storage bin will not experience cementation and blockage. In order to improve the accuracy of the experiment, supplementary testing was conducted on the bonding state of the material in the storage bin when $P_4 = 4.5kN$. When the stress entered a constant pressure state, the strain change stabilized at 0.07, and the gangue could not be completely poured out at once. The lower part showed a certain bonding situation, so under this load, the lower part of the storage bin would still experience blockage.

Considering a certain safety factor, choose 4kN as the boundary value for gangue bonding, and the load of 4kN means that the stress reaches 0.5MPa. Therefore, the internal storage height of the storage bin is:

$$h_a = P_3 \times \frac{100}{\rho_a}$$

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Where: $P_3$ is 0.5MPa; When calculating the true density of gangue, $\rho_a = 2.5$, and when calculating the apparent density of gangue, $\rho_a = 1.446$. After calculation, the internal storage heights of the storage bin are 20m and 34.5m, respectively. Therefore, considering safety factors, the final alarm height of the storage bin is 20m.

5. Conclusions

(1) After the secondary crushing of the gangue in Hulushu Coal Mine, the porosity of the gangue is 7%~11%, the minimum porosity is 7.12%, the maximum porosity is 10.595%, and the average porosity is 8.58%. Through the compaction experiment of naturally graded gangue, it is believed that the rock compression process can be divided into two stages: the macro pore fissure compaction stage and the micro pore fissure development and destruction stage. It is proposed that the elastic modulus plays a decisive role in the compression characteristics of gangue particles.
(2) According to the specific working conditions of the gangue waste storage and the experimental phenomenon of natural particle size grading, it was found that when all loads were below 4kN, there was no cement blockage phenomenon in the gangue, and the corresponding height was 20m. Therefore, the alarm height of the storage bin should be set at 20m.

(3) The stress-strain curves of the B1 ~ B6 gangue compression test were fitted, and according to Fig. 5b, it can be seen that the elastic modulus of the B1 ~ B6 experimental group showed a monotonic increase trend, and the final deformation variable showed a trend of first increasing and then decreasing. Therefore, the larger the particle size of gangue and the higher the proportion of large particle size gangue, the more conducive it is to the stability of the load-bearing structure. Due to the coupling effect of the fragmentation of large particles and the synergistic loading of particles with different sizes, the final deformation of the sample shows a trend of first increasing and then decreasing.

(4) By drawing the strain energy density curve, it is concluded that there are mainly slow energy consumption stage, accelerated energy consumption stage and rapid energy consumption stage in the process of particle compression. Before $\varepsilon = 0.110$ the strain energy density increases with the increase of particle diameter. In the later stage of compression, the strain energy density of the sample is B1, B2, B6, A5, B5, B4 from high to low. The strain energy density of the sample presents a "U" shape, and the strain energy density of B1, B2, B6 groups is larger. By fitting the initial elastic modulus and final deformation curve, the estimated values of B3 group samples were obtained, and it was found that the support effect of B1, B2, and B6 group gangue samples was good. Through the analysis of the particle crushing energy of the sample, it was found that the B6 group requires the least amount of energy and has the best economic benefits. Therefore, the B6 group sample is the most suitable filling material.

(5) When analyzing the control effect of overlying rock from the perspective of filling rate, it was found that the filling rate of the filling material is mainly influenced by the particle size and quantity of the largest particle in the material. The larger the size of the larger particles, the higher the content, and the greater the ability of the filling material to resist deformation. The filling rates of the B1, B2, B4, B5, B6, and A5 groups of samples are 70.3%, 72.7%, 75.8%, 75.5%, 84.6%, and 76.7%, respectively, with the B6 group having the best filling effect.

**Declarations**

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**Data Availability:** The Microsoft Excel Worksheet data used to support the findings of this study are available from the corresponding author upon request.

**References**


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Figure 5

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Selection of pressure equalizing measuring line at the bottom of the storage bin