Study on the Self–Bearing Mechanism and Mechanical Properties of Gangue Slurry under Overburden Loading

Sixu Liu, Jianfei Xu *, Nan Zhou, Yuzhe Zhang, Chaowei Dong and Zhuo Lv

Abstract: The mining of coal resources is accompanied by a large amount of solid waste such as gangue, which seriously affects the ecological environment. The gangue grouting backfilling technique can achieve the dual goals of gangue disposal and surface deformation control by injecting gangue slurry into the underground. The bearing mechanical characteristics of gangue slurry directly affect the surface deformation control effect of the grouting backfilling technique. In this study, a loading simulation system of grouting backfilling materials was designed, uniaxial confined compression tests were conducted, and the self–bearing mechanism of large particle–sized gangue slurry with different fluidities under instantaneous and creep loading modes was investigated. Additionally, the mechanical characteristics of the compacted body (i.e., the gangue slurry after creep loading) were analyzed. The results indicate that the self–bearing process of gangue slurry can be divided into three stages: the rapid compression and drainage stage, the pore compaction and water bleeding stage, and the particle crushing and elastic–plastic deformation stage. The uniaxial compressive stress–strain curve of a compacted body can be classified into four stages: elastic stage, yield stage, reinforcement stage, and crushing stage, and the strength of the compacted body is affected by the loading time and fluidity of the slurry. When the slurry with a fluidity of 240 mm is subjected to constant pressure for 3 h, the compressive strength of the slurry reaches the maximum value of 4.98 MPa, and 13.1% stress damage occurs when the constant pressure reaches 4 h. This research provides a theoretical basis for the improvement of the proportion and bearing characteristics of gangue grouting materials.

Keywords: gangue grouting backfilling; load–bearing deformation characteristics; self–bearing mechanism; mechanical strength of compacted body

1. Introduction

The extraction of coal resources is often accompanied by the generation of solid waste products such as coal gangue, which brings many challenges to society and the environment. The large–scale discharge of gangue results in a range of issues, including land resource occupation, human health hazards, and surface desertification [1–5]. Furthermore, the movement and fracturing of overburden after coal mining leads to surface deformation and damage to buildings [6–10]. The disposal of gangue and control of surface deformation have become increasingly difficult problems in the protection of the mining ecological environment. In the gangue grouting backfilling technique [11], the backfilling slurry is prepared by mixing the gangue with different particle sizes and water at different ratios, and then transported to the underground backfilling area by filling equipment and pipelines. The distinguishing feature of this technique lies in the absence of additives in the backfilling slurry. The backfilling area includes the caving zone, fracture zone, and separation zone formed after coal mining. The backfilling effect is mainly affected by the bearing characteristics of the slurry. The on–site application research of the grouting backfilling technique shows [12] that the backfilling material flows in the form of slurry in the area during the grouting process; as the overburden slowly sinks, the water in the slurry
continuously bleeds under pressure, ultimately forming a compacted body with certain strength. In this case, the compacted body remains in the backfilling area and plays a role in controlling surface deformation. The compression deformation and water bleeding of the slurry under pressure directly affect the effectiveness of the grouting backfilling technique in controlling the surface. Therefore, studying the bearing mechanism and mechanical properties of backfilling materials underground is of great significance.

At present, research on the bearing deformation characteristics of backfilling materials (including solid and cementitious materials) has been extensively conducted from both theoretical and on-site perspectives. In terms of solid backfilling materials, Wu Dongtao et al. [13–18] studied the bearing deformation characteristics and failure laws of solid waste under different particle size gradings, lateral confinement methods, and other conditions from both macro and micro perspectives through physical experiments, numerical simulations, and other methods. Zhang Qingfeng et al. [19,20] investigated the crushing characteristics of gangue backfilling under different pressure conditions based on the on-site application of the solid backfilling technique. Ekrem Kalkan et al. [21,22] analyzed the effect of additives on improving the strength characteristics of solid waste by adding materials such as silicon powder and fly ash to solid waste. For cementitious backfilling materials, Pierre Estephane et al. [23–25] explored the influence of the water content, fine particle size ratio, and shape of solid particles on the porosity, load–bearing performance, plasticity, and mechanical strength of cementitious backfilling materials after solidification. Gu Tianfeng et al. [26,27] obtained the compressive strength of cement coal gangue grouting materials activated by additives through physical experiments and analyzed the strengthening effect of cement on cementitious backfilling materials. Murat Ozturk et al. [28] tested the mechanical properties of cementitious backfilling materials by replacing cement with materials such as slag, fly ash, and silicon powder, and compared the strength of backfilling materials under different replacement materials and curing ages. The research results have shown that changing particle size grading, additives, and loading methods can affect the mechanical bearing characteristics of solid and cementitious backfilling materials. However, there is little research on the mechanical properties of slurry materials made from gangue and water.

Based on the gangue grouting backfilling technique, a loading simulation system of grouting backfilling materials was designed, and differences in the water bleeding rate of gangue grouting backfilling materials during static and loading processes were compared in this study. In addition, two loading methods (instantaneous loading and creep loading) were designed, the bearing characteristics of the backfilling material under the conditions of instantaneous collapse of the roof and slow subsidence of the overburden on site were simulated, and the changes in porosity of the backfilling material during the entire compression process were analyzed. Finally, the uniaxial compressive strength of the compacted body formed after compaction of the backfilling material was tested, and the influence of fluidity on the later mechanical strength of the gangue grouting backfilling material was analyzed.

2. Materials and Methods

2.1. Material Properties

2.1.1. Particle Size Grading of Gangue

The gangue grouting backfilling material was made by mixing and stirring crushed gangue with water, and no additives were added. The gangue used in the experiment was taken from the washing gangue generated during the mining process of a certain coal mine. To ensure the good conveying performance of the gangue slurry, the fluidity should be controlled between 220 and 260 mm [29]. Under the constant mass concentration (70%) of the slurries, five slurries with different fluidities were obtained by adjusting the particle size grading of the aggregates. Figure 1 shows the particle size grading of the gangue. The characteristic particle size parameters of the gangue with different fluidities
where \(d\) were calculated from Figure 1, including the controlled particle size \((d_{10}, d_{30} \text{ and } d_{60})\), non–uniformity coefficient \((C_u)\), and curvature coefficient \((C_c)\), as shown in Table 1.

![Figure 1. Curves for particle size grading of gangue.](image)

**Table 1.** Particle size parameters of gangue under different fluidities.

<table>
<thead>
<tr>
<th>Characteristic Parameter</th>
<th>(d_{10})</th>
<th>(d_{30})</th>
<th>(d_{60})</th>
<th>(C_u)</th>
<th>(C_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluidity–220 mm</td>
<td>0.05</td>
<td>0.10</td>
<td>0.14</td>
<td>2.8</td>
<td>1.43</td>
</tr>
<tr>
<td>Fluidity–230 mm</td>
<td>0.05</td>
<td>0.11</td>
<td>0.19</td>
<td>3.8</td>
<td>1.27</td>
</tr>
<tr>
<td>Fluidity–240 mm</td>
<td>0.05</td>
<td>0.11</td>
<td>0.21</td>
<td>4.2</td>
<td>1.15</td>
</tr>
<tr>
<td>Fluidity–250 mm</td>
<td>0.05</td>
<td>0.11</td>
<td>0.23</td>
<td>4.6</td>
<td>1.05</td>
</tr>
<tr>
<td>Fluidity–260 mm</td>
<td>0.05</td>
<td>0.12</td>
<td>0.23</td>
<td>4.6</td>
<td>1.25</td>
</tr>
</tbody>
</table>

As shown in Figure 1, the main factor affecting the fluidity of gangue slurry is the proportion of coarse and fine particle sizes. The smaller the proportion of fine particle sizes, the greater the fluidity of the slurry. According to Table 1, the particle size grading of gangue with different fluidities is relatively uniform, and the gradation continuity is good.

2.1.2. True Density of Gangue

The pyknometer method was used to test the true density of gangue by Equation (1).

\[
d = \frac{M d_s}{M + M_2 - M_1}
\]

where \(d\) is the true density of the sample, \(g/cm^3\); \(M\) is the mass of the sample, \(g\); \(M_1\) is the weight of the pyknometer, sample, and distilled hydration, \(g\); \(M_2\) is the weight of specific gravity bottle and full bottle distilled hydration, \(g\); \(d_s\) is the density of distilled water at room temperature, and \(d_s \approx 1 \text{ g/cm}^3\).

2.1.3. Mesoscopic Characteristics of Gangue

Figure 2 shows the scanning electron microscope (SEM) test results of the gangue material. As shown in Figure 2a, the proportion of granular small particle size gangue is higher among the granular gangue, and it is deposited in the lower layer of the tested sample. The large particle size gangue is dispersed in the upper part of the tested sample. The gangue particles with different sizes interlock and fill each other. As shown in Figure 2b, the gangue has an irregular block structure, loose intergranular structure, abundant pores, and a large number of pore structures. This indicates that the gangue has a significant compressibility.
The bottom of the system is arranged with a bleeding channel to guide the bleeding water. Pressure structure, a filtering structure, and a bleeding structure.

During the compression process, water in the slurry can be secreted and the loss of solid particles can be prevented. A loading simulation system of grouting backfilling materials was developed to simulate the bleeding and bearing characteristics of the gangue slurry after loading on the overburden in the backfilling area, as shown in Figure 4. The system mainly includes a pressure structure, a filtering structure, and a bleeding structure. ① Pressure structure. This structure includes a pressure rod, vertical hole, piston, sealing ring, and compression chamber. The pressure rod and the piston arranged with a sealing ring transmit the pressure of the universal testing machine to the slurry inside the compression chamber, playing a role in pressurization. The vertical holes inside the compression rod are used to inject the slurry into the compressed slurry. ② Filtering structure. This structure includes a stainless steel mesh with a pore size of 0.1–1 mm in the upper layer, a screen cloth of 18–25 µm in the middle layer, and a screen plate with a thickness of 2 mm, a hole diameter of 2 mm, and a hole spacing of 2 mm in the lower layer. During the compression process, water in the slurry can be secreted and the loss of solid particles can be prevented. ③ Bleeding structure. The bottom of the system is arranged with a bleeding channel to guide the bleeding water to the weighing device. The loading simulation system of grouting backfilling materials

2.2. Test Equipment

A loading simulation system of grouting backfilling materials was developed to simulate the bleeding and bearing characteristics of the gangue slurry after loading on the overburden in the backfilling area, as shown in Figure 4. The system mainly includes a pressure structure, a filtering structure, and a bleeding structure. ① Pressure structure. This structure includes a pressure rod, vertical hole, piston, sealing ring, and compression chamber. The pressure rod and the piston arranged with a sealing ring transmit the pressure of the universal testing machine to the slurry inside the compression chamber, playing a role in pressurization. The vertical holes inside the compression rod are used to inject the slurry into the compressed slurry. ② Filtering structure. This structure includes a stainless steel mesh with a pore size of 0.1–1 mm in the upper layer, a screen cloth of 18–25 µm in the middle layer, and a screen plate with a thickness of 2 mm, a hole diameter of 2 mm, and a hole spacing of 2 mm in the lower layer. During the compression process, water in the slurry can be secreted and the loss of solid particles can be prevented. ③ Bleeding structure. The bottom of the system is arranged with a bleeding channel to guide the bleeding water to the weighing device. The loading simulation system of grouting backfilling materials

2.1.4. Mineral Composition of Gangue

The X-ray diffraction (XRD) spectrum of the gangue material is shown in Figure 3. By comparing it with the international powder diffraction database, it can be obtained that the main mineral composition of the gangue is quartz (quartz, the main component of sandstone), kaolinite (kaolinite, an important component of mudstone), and muscovite (muscovite, an important component of mudstone). Therefore, the gangue used in the experiment is mainly composed of sandstone and mudstone.

![Figure 2. SEM results of gangue materials: (a) 500×, (b) 5000×.](image)

![Figure 3. XRD test results of gangue materials.](image)

![Figure 2. SEM results of gangue materials: (a) 500×, (b) 5000×.](image)

![Figure 3. XRD test results of gangue materials.](image)
has an inner diameter of 130 mm, a height of 200 mm, a piston thickness of 50 mm, an effective inner cavity height of 150 mm, and a maximum pressure resistance value of 32 MPa. The hardness and stiffness of the cylinder wall of the loading simulation system of grouting backfilling materials are large and the wear resistance is strong. Therefore, the radial and lateral deformation in the test can be ignored. The WAW–2000D universal testing machine serves as a testing loading device, with servo control and automatic data acquisition functions. The axial pressure range is 0.02–2000 kN, and the loading rate range is 0.002–20 kN/s.

Figure 4. The loading simulation system of grouting backfilling materials.

2.3. Test Schemes
2.3.1. Test Steps

The bearing deformation characteristics of gangue slurry were obtained by uniaxial confined compression tests on the gangue slurry loaded into the loading simulation system through the WAW–2000D universal testing machine. In the later stage of mechanical strength testing, the WAW–1000 universal testing machine was used to conduct uniaxial compressive strength tests on the compacted body. Figure 5 shows the testing steps.

Figure 5. Test steps.

(1) Equipment debugging and installation. The sieve plate, sieve step, and sieve mesh were placed on the base from bottom to top and fixed with bolts to the compression chamber. The piston connected to the pressure rod was placed inside the compression chamber and lubricating oil was evenly applied on the contact part between the two.

(2) Preparation and pouring of slurry. According to the particle size ratio, 2.8 kg of gangue aggregate and 1.2 kg of water were weighed, mixed, and stirred to obtain 4 kg of
slurry with a concentration of 70%. Then, the slurry was poured into the compression chamber along the vertical hole in the pressure rod until it reached the experimental design height. To reduce errors, the slurry was injected in four stages, and after each injection, the loading simulation system of grouting backfilling materials was vibrated. After the slurry was evenly distributed, the next injection was conducted again.

3) Instrument installation and testing. The loading simulation system of grouting backfilling materials was placed on the workbench of the WAW–2000D universal testing machine, and the bleeding channel was connected to the water pipe. The other end of the water pipe was connected to the weighing container. Subsequently, the universal testing machine was started, and the slurry was subjected to loading.

4) Sample maintenance and drilling. The compacted body formed by the creep compression of the gangue slurry was placed in a curing box and cured for 28 days. The compacted body was sampled and cut using a drilling prototype and cutting machine.

5) Uniaxial compressive strength test. The uniaxial compressive strength of the compacted body was tested using the WAW–1000D rock testing system. The specimen was placed in the center of the pressure plate of the material testing machine, and the spherical seat was adjusted to align the centerline of the upper and lower pressure plates of the testing machine and the specimen. Loading was initiated at a speed of 0.02 mm/s until sample failure occurred, and the specimen failure load was recorded.

2.3.2. Test Schemes

When the burial depth of the coal seam was 800 m, the pressure exerted by the dead weight of overburden on the coal seam was about 20 MPa. In order to meet the conditions of most mines, the axial stress threshold for the test was designed to be 20 MPa, and the loading speed was 4.9 kPa/s. To ensure the operability and reliability of the experiment, the injection height of the slurry was designed to be 150 mm (i.e., 3/4 of the compression chamber height).

(1) Instantaneous loading scheme

In the test, the slurry was compacted by loading at a constant speed and setting a threshold. When the pressure reached the threshold, the loading was immediately stopped. The experimental groups of slurry with fluidity of 220–250 mm are sequentially marked as I1–I5, and the compression bleeding and stress–strain data of the slurry during the experiment were recorded.

(2) Creep loading scheme

In the experiment, a graded loading method was adopted at four levels of 5, 10, 15, and 20 MPa. The loading duration of each level was about 1000 s, and the loading duration was set as x. The creep loading method was achieved and data were recorded. Figure 6 shows the loading method and Table 2 shows the test plan.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Fluidity/mm</th>
<th>x</th>
<th>Grouting Height h0/mm</th>
<th>Loading Rate/kPa × s−1</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1–1h</td>
<td>220</td>
<td>1</td>
<td>150</td>
<td>4.9</td>
</tr>
<tr>
<td>C1–2h</td>
<td>220</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1–3h</td>
<td>220</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1–4h</td>
<td>220</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2–1h</td>
<td>230</td>
<td>1</td>
<td>150</td>
<td>4.9</td>
</tr>
<tr>
<td>C2–2h</td>
<td>230</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2–3h</td>
<td>230</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2–4h</td>
<td>230</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3–1h</td>
<td>240</td>
<td>1</td>
<td>150</td>
<td>4.9</td>
</tr>
<tr>
<td>C3–2h</td>
<td>240</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3–3h</td>
<td>240</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3–4h</td>
<td>240</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4–1h</td>
<td>250</td>
<td>1</td>
<td>150</td>
<td>4.9</td>
</tr>
<tr>
<td>C4–2h</td>
<td>250</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4–3h</td>
<td>250</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4–4h</td>
<td>250</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5–1h</td>
<td>260</td>
<td>1</td>
<td>150</td>
<td>4.9</td>
</tr>
<tr>
<td>C5–2h</td>
<td>260</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5–3h</td>
<td>260</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5–4h</td>
<td>260</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Constant speed and pressure loading scheme.
Table 2. Test scheme for creep bearing deformation characteristics of slurry.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Fluidity/mm</th>
<th>$\times$</th>
<th>Grouting Height $h_0$/mm</th>
<th>Loading Rate/kPa $\times s^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1–1h</td>
<td></td>
<td>1</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>C1–2h</td>
<td></td>
<td>1</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>C1–3h</td>
<td></td>
<td>1</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>C1–4h</td>
<td></td>
<td>1</td>
<td>240</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Test plan for later mechanical strength of the compacted body.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Diameter/mm</th>
<th>Height/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1–1</td>
<td>48.4</td>
<td>50.4</td>
</tr>
<tr>
<td>S1–3</td>
<td>48.6</td>
<td>70.0</td>
</tr>
<tr>
<td>S2–1</td>
<td>48.4</td>
<td>60.0</td>
</tr>
<tr>
<td>S2–2</td>
<td>48.4</td>
<td>59.8</td>
</tr>
<tr>
<td>S2–3</td>
<td>48.6</td>
<td>68.8</td>
</tr>
<tr>
<td>S2–4</td>
<td>48.4</td>
<td>60.0</td>
</tr>
<tr>
<td>S3–1</td>
<td>48.6</td>
<td>50.2</td>
</tr>
<tr>
<td>S3–2</td>
<td>48.6</td>
<td>59.7</td>
</tr>
<tr>
<td>S3–3</td>
<td>48.8</td>
<td>60.8</td>
</tr>
<tr>
<td>S3–4</td>
<td>48.6</td>
<td>59.9</td>
</tr>
<tr>
<td>S4–1</td>
<td>48.6</td>
<td>50.6</td>
</tr>
<tr>
<td>S4–2</td>
<td>48.2</td>
<td>59.8</td>
</tr>
<tr>
<td>S4–3</td>
<td>48.6</td>
<td>59.8</td>
</tr>
<tr>
<td>S4–4</td>
<td>48.6</td>
<td>60.4</td>
</tr>
<tr>
<td>S5–2</td>
<td>48.2</td>
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<td>S5–3</td>
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<td>69.7</td>
</tr>
<tr>
<td>S5–4</td>
<td>48.4</td>
<td>70.3</td>
</tr>
</tbody>
</table>

(3) Test schemes for mechanical strength

After the creep loading test of the gangue slurry, the compacted body was placed in a curing box and cured under a constant temperature of 20 °C and constant humidity of 99% RH for 28 days. Subsequently, the mechanical strength test was carried out by drilling specimens and the sample was subject to loading at a speed of 0.02 mm/s until sample failure occurred, and the failure load of the specimens was recorded. Table 3 shows the test plan for the later mechanical strength of the compacted body.

Table 3. Test plan for later mechanical strength of the compacted body.

2.3.3. Parameter Measurement Methods

After compression, the deformation and water content of the slurry material underwent significant changes. In this experiment, the compressive bleeding rate and compres-
sion rate were taken as the characterization parameters of the bearing deformation of the gangue slurry, and the compressive strength was taken as the characterization parameter of the later mechanical strength of the slurry. The calculation equations for different parameters are as follows:

1. Compression rate

\[ \lambda = \frac{\Delta h}{h} \times 100\% \]  

where \( \lambda \) is the compression rate; \( \Delta h \) is the height of deformation supported by the slurry, mm; and \( h \) is the initial height of the slurry injected into the backfill deformation monitoring device, mm.

2. Compressive bleeding rate

\[ B = \frac{m_b}{m_w} \times 100\% \]  

where \( B \) is the compressive bleeding rate; \( m_b \) is the amount of water bleeding, g; and \( m_w \) is the moisture content of the gangue slurry, g.

3. Later mechanical strength

\[ R_C = \frac{P}{F} \times 10^{-6} \]  

where \( R_C \) is the uniaxial compressive strength of the specimen, MPa; \( P \) is the failure load of the specimen, N; and \( F \) is the initial compressive area of the specimen, cm².

3. Results and Discussion

3.1. Bearing and Deformation Characteristics of Gangue Slurry

3.1.1. Change of Compression Rate

1. Instantaneous loading

Based on the data obtained from the experiment, the compression rate stress curve of the gangue slurry under instantaneous loading conditions was calculated using Equation (2), as shown in Figure 7.

![Figure 7. Compression rate–stress curve of gangue slurry under the instantaneous compression test.](image-url)

As shown in Figure 7, it can be seen that:

1. During the instantaneous loading process, the axial compression rate of gangue slurry with different fluidities is approximately an exponential function of stress, and there is a deformation threshold. In addition, the deformation threshold is negatively correlated with the fluidity.

2. The deformation threshold of I4 and I5 is lower than 20 MPa, and the entire process of compression rate change can be divided into three stages:
Stage I. Rapid deformation stage (0–4 MPa). The compression rate increases rapidly with the increase of stress, and the deformation generated in this stage accounts for about 45% of the total deformation. In the initial loading stage, the slurry has large pores and poor stability, and the contact area and compression degree of gangue particles are small, exhibiting characteristics of rapid deformation and poor bearing performance. At this stage, the compression rate–stress curves of I4 and I5 almost overlap, and the degree of bearing deformation of the slurry is less affected by the fluidity.

Stage II. Slow deformation stage (4–14 MPa). The compression rate decreases with the increase of stress, and it gradually decreases with the increase in deformation degree. The compression deformation of gangue slurry mainly occurs in this stage, accounting for about 50%. At this stage, the compression rate of I4 increases slower than that of I5, and the influence of fluidity on the deformation of the slurry increases. There are significant differences in the load-bearing deformation capacity of different slurries. The pores in the slurry decrease with the increase in compression rate, and the gangue particles undergo crushing and backfilling under pressure, resulting in close contact. The positions between particles are relatively balanced, and the resistance to deformation is enhanced.

Stage III. Stable deformation stage (14–20 MPa). After entering this stage, the compression rate–stress curve is almost parallel, the compression rate tends to a constant value, and the deformation that occurs when the stress increases is almost zero. The difference in compression rates between I4 and I5 during this stage decreases compared to that in the slow deformation stage. After the compression rate reaches the threshold, the broken small particles have filled the pores, forming a stable pore structure. At this time, the elastic–plastic structure of the slurry changes under stress, affecting its later mechanical strength.

3. The deformation threshold of I1–I3 is higher than 20 MPa. Throughout the entire transformation process, the slurry only goes through the rapid deformation stage and the slow deformation stage. When the stress is loaded to 20 MPa, the stable stage is not reached, while the compression rate shows a stable trend. Compared to the deformation process of I4 and I5 slurries, the rapid deformation stage of I1–I3 slurries is shorter and their proportion of deformation is smaller, while the slow deformation stage of I1–I3 slurries lasts longer and their proportion of deformation is larger.

4. The compression rate of slurries with different fluidities increases with the increase of fluidity. When the axial stress reaches 20 MPa, the extreme values of compression rate are 32%, 42%, 45%, 53%, and 55%, respectively. Based on the analysis of the particle size grading of gangue in Figure 1, it can be concluded that the greater the fluidity of the slurry, the higher the proportion of fine-grained gangue, the greater the deformation degree of the slurry after compression, and the poorer the deformation bearing capacity of the compacted body.

(2) Creep loading

Figure 8 shows the compression rate–time curve of gangue slurry under creep loading conditions.

As shown in Figure 8, it can be seen that:

1. The compression rate of the slurry after creep loading does not exceed 50%. Under different loading schemes, the compression rate of the slurry increases with the increase in fluidity, and with the increase of \( x \), the compression rate of the slurry with the same fluidity also increases. Throughout the entire loading process, the compression rate changes with time in three stages: rapid deformation, slow deformation, and stable deformation. The rapid deformation stage mainly occurs during the first loading pro-
cess. When entering the subsequent loading stage, the rate of increase in compression rate significantly decreases.

2. As \( x \) increases, the grouping differences in compression rates between slurries with different fluidities gradually weaken over time. When \( x = 1 \), the compression rates of \( C1–C2 \) and \( C4–C5 \) remain significantly different, and \( C1–C2 \) does not reach a stable stage when loaded to 20 MPa. When \( x = 2 \) and 3, the difference in compression rates between \( C1–C2 \) and \( C4–C5 \) gradually decreases. When \( x = 4 \), the difference in compression rates between \( C1–C2 \) and \( C4–C5 \) further decreases, and compression rates of \( C1–C5 \) have reached a stable stage when loaded to 20 Mpa. Under different loading schemes, the extreme variation of the compression rate of \( C3 \) is relatively small, and the trend of variation over time is relatively stable. This indicates that the gangue slurry has good bearing performance and deformation resistance when the fluidity is 240 mm.

3. Compared with instantaneous loading, the compression deformation range of slurry under creep loading conditions is smaller and more stable. The compacted body after loading has a larger spatial support height, stronger deformation resistance, and bearing capacity.

3.1.2. Change Law of Compressive Bleeding Rate

(1) Instantaneous loading

The bleeding rate of the gangue slurry after static and instantaneous loading can be calculated by Equation (3), as shown in Figure 9. Figure 10 shows the compressive bleeding rate stress change curve of the gangue slurry during the instantaneous loading process.
As shown in Figure 9, the static bleeding rate and compressive bleeding rate of the gangue slurry are positively correlated with fluidity. The bleeding rate of the slurry is low in a static state, only 3.37–9.00%. The moisture in the slurry can maintain its good conveying performance. The bleeding rate of the slurry after loading increases significantly, reaching 59.89–72.07%. Specifically, I1–I5 slurries increase by 56.52%, 59.63%, 58.54%, 50.77%, and 72.07%, respectively. When the stress reaches 20 Mpa, the water content in the slurry is less than 45%, and the water remaining in the slurry and gangue particles form a high solid–water ratio compacted body, which plays a bearing role under the loading of overburden.

As shown in Figure 10, during the instantaneous loading process, the compressive bleeding rate of the gangue slurry with different fluidities is approximately an exponential function of stress, and there is a bleeding threshold. In addition, the bleeding threshold is negatively correlated with the fluidity. The entire process of compressive bleeding rate of slurries under the loading changes with strain, which can be divided into three stages:

1. Supersaturated drainage stage (0–4 Mpa): the compressive bleeding rate increases rapidly with the increase of stress, and in the early stage of loading, the compressive bleeding rates of slurries with different fluidities vary slightly, but still increase with the increase of fluidity. Before loading, the slurry is in a supersaturated state, with most of the water being free water. After being compressed in an unsealed space, water is quickly discharged through a drainage pipeline and the slurry does not have a bearing effect. At this stage, the slurry is mainly pressurized by pore water, and its bearing performance is poor.
Compressive bleeding stage (4–12 Mpa): the compressive bleeding rate increases with the increase of stress decreases. This mainly affects the difference in the final bleeding rate between slurries with different fluidities. The smaller the fluidity, the earlier it enters this stage. After the first stage of loading, all the supersaturated water in the slurry has been discharged, and the remaining water mainly exists in the form of pore water. Under the loading, a water film is formed on the surface of the gangue particles, promoting the sliding and backfilling of the gangue. As the stress continues to increase, the pores in the slurry decrease, and pore water is secreted under loading. The gangue particles of slurry gradually play a dominant bearing role.

No bleeding stage (12–20 Mpa): the bleeding rate–stress curve in this stage is almost parallel, and the proportion of the compressive bleeding rate with increasing stress is almost zero. It indicates that there is no more water bleeding. After the first two stages of loading, the content of pores and pore water tends to be constant, and the slurry essentially transforms into a compacted state with a stable ratio of solid to water. Afterward, the gangue particles undergo fragmentation under the continuously increasing stress, and the elastic–plastic structure of the slurry changes, mainly affecting the mechanical properties of the compacted body after the loading.

Creep loading

Figure 11 shows the compressive bleeding rate of gangue slurry with different fluidities under creep loading conditions.

As shown in Figure 11, it can be seen that:

1. Under creep loading conditions, the compressive bleeding rate of the slurry exceeds 50%, and under the same loading scheme, it increases with the increase of fluidity. Among them, the compressive bleeding rates of C1 and C2 show a decreasing–increasing–decreasing trend with the increase of constant pressure loading time, C3 shows an increasing–decreasing–increasing trend, and C4 and C5 show an increasing–decreasing trend. There is a significant change mainly in the loading scheme $x = 2$. This suggests that the bleeding characteristics of the slurry under the creep loading are jointly affected by the fluidity and constant pressure time. When the slurry is at low fluidity and the constant pressure time is short, the fluctuation of the compressive bleeding rate is significant with the change in loading time. When the fluidity is high or the constant pressure time is long enough, the compressive bleeding rate of the slurry shows an increasing trend with the increase in loading time.

2. Compared to those under instantaneous loading conditions, the compressive bleeding rate of the slurry after creep loading is in a lower range and is not positively correlated with fluidity. During the constant pressure stage of creep loading, water is trapped in the pores of the gangue particles under pressure, effectively improving the defor-
mation resistance and bearing performance of the gangue slurry. Consequently, the mechanical strength of the compacted body is significantly improved.

3.2. Self–Bearing Mechanism of Gangue Slurry

Based on the variation characteristics of various parameters in the experiment, the self–bearing mechanism of the gangue slurry is obtained, as shown in Figure 12.

As shown in Figure 12, the self–bearing and deformation process of gangue slurry can be divided into three stages.

Stage I: rapid compression and drainage stage. The water in the gangue slurry mainly exists in the form of free water, and the relative position of the gangue particles is loose, with large pores in the slurry. When subjected to pressure, the vast majority of supersaturated water is quickly discharged, and the gangue particles are not yet compressed at this time. The pore water in the slurry plays a main role in load–bearing, and the slurry has poor stability under loading. At this stage, the fast water bleeding and compression deformation rate of the slurry are the main features.

Stage II: pore compaction and water bleeding stage. After the first loading stage, the bearing effect of the gangue particles is affected by water, and the pores of the slurry are continuously compacted with water bleeding. Water forms a water film on the surface of gangue particles under pressure, which has a lubricating effect, reduces the frictional resistance between particles, and facilitates the sliding and backfilling of gangue particles. Since the main components of gangue are sandstone and mudstone, the strength of gangue particles is degraded under the action of water wedge, dissolution, and softening, accelerating particle fragmentation and further densifying pores. The water bleeding in this stage is mainly the combined water discharged under pressure. Compared with the first stage, the growth rate of the bleeding rate and compression rate in this stage gradually decrease.

Stage III: particle crushing and elastic–plastic deformation stage. After the loading stress of the gangue slurry reaches the threshold, the bleeding rate and porosity tend to extreme value with minimal changes. The backfilling material almost transforms from a slurry to a compacted solid with a stable solid–water ratio, and the water retained in the compacted solid plays a bearing role with the crushed gangue particles in the form of bound water. As the stress continues to increase within a certain range, compression occurs between gangue particles, and gangue is tightly connected through point contact or mutual meshing. Point contact generates stress concentration, leading to elastic–plastic failure of particles. Broken small particles fill the pores, gradually reducing the porosity and significantly enhancing the resistance to deformation. The contact points increase with the increase in external load, and the number of contact points increases. It leads to an increase in the pressure increment necessary for the relative deformation to continue. Additionally, the contact between particles evolves from sharp angle contact to obtuse

![Figure 12. Self–bearing mechanism of gangue slurry.](image-url)
angle contact, spherical contact, or meshing contact. The average stress between particles decreases, the particle bearing capacity gradually increases, and the gangue transforms into a continuous medium, resulting in the hardening phenomenon.

3.3. Later Mechanical Strength of Compacted Body

The compacted solid obtained from slurries with different fluidities under pressure has differences in height. As a result, some samples do not meet the requirements of the standard sample (GB/T50266–99). The parameters obtained from the test are standardized according to the height-to-diameter ratio formula (Equation (5)).

\[ \sigma_1 = \frac{8\sigma_2}{7 + 2\frac{D}{H}} \]  

(5)

where \( \sigma_1 \) is the uniaxial compressive strength of the standard specimen, Mpa; \( \sigma_2 \) is the uniaxial compressive strength of non-standard specimens, Mpa; \( D \) is the non-standard sample diameter, mm; \( H \) is the height of the non-standard specimen, mm.

According to the experimental data, the compressive strength of the compacted body is calculated using Equations (4) and (5), as shown in Figure 13. Since the specimens were not drilled from the compacted body with slurry fluidities of 220 mm and 260 mm, Figure 14 shows the uniaxial compressive stress-strain curve of the compacted body with a fluidity of 230–250 mm.

As shown in Figure 13, when the fluidity is constant, the compressive strength of the compacted solid increases with the increase of loading time in the range of \( x = 1–3 \). When \( x = 3 \), the compressive strength is 3.06 MPa, 3.77 MPa, 4.98 MPa, 4.62 MPa, and 4.54 MPa, respectively. When \( x = 4 \), the backfilling material undergoes stress damage after prolonged loading, resulting in a decrease in the strength of the compacted body, but it is not lower than that when \( x = 1–2 \). Moreover, the greater the fluidity, the more significant the degree of strength loss. The loss proportion of the compacted body with a fluidity of 230–260 mm is 8.5%, 13.1%, 18.2%, and 18.7%, respectively. When the loading scheme is the same, the compressive strength of the slurry increases first and then decreases as the flow increases, and the compressive strength with a fluidity of 240 mm is the maximum value. This indicates that when the fluidity is 240 mm and the creep loading scheme is \( x = 3 \), the mechanical properties of the compacted body in the later stage are the best. In addition, when the fluidity increases to 250 mm, \( C_u \) is the maximum value and \( C_c \) is the minimum value, there are fewer small particle sizes and more large particle sizes of gangue. When \( x = 1–2 \), as well as the short compression time of the slurry, there are more pores in the compacted body, resulting in lower strength and a significant decrease in the strength of the compacted body. As illustrated in Figure 14, the overall trend of stress-strain changes of the
compacted body before and after fragmentation is consistent. The entire loading process can be divided into four stages. (1) Elastic stage (OA section): in this stage, the stress increases linearly with strain. (2) Yield stage (AB section): in this stage, the stress continues to increase with increasing strain, but the degree of increase is significantly lower than that in the elastic stage. (3) Reinforcement stage (BC section): in this stage, stress increases rapidly with increasing strain, and the degree of increase is higher than that in the elastic stage. (4) Crushing stage: in this stage, the stress begins to drop after reaching its peak, and residual stress exists after the peak. During the entire pre-peak (OC section) loading process, the proportion of the reinforcement stage (BC section) is higher and exhibits a linear growth curve similar to the elastic stage. At this time, the compacted body undergoes local plastic failure, causing stress to redistribute until the stress peak is reached.

Figure 14. Stress–strain curves of compacted solid with different fluidities: (a) 230 mm, (b) 240 mm, (c) 250 mm.

4. Conclusions

In this study, a loading simulation system of grouting backfilling materials was used to conduct uniaxial confined compression tests on gangue slurry with five different fluidities. The main conclusions are as follows:

(1) Under instantaneous loading conditions, the compression rate of gangue slurry changes with stress, which can be divided into rapid the deformation stage, slow deformation stage, and deformation stable stage. The lower the fluidity, the greater the corresponding stress when the slurry reaches the deformation stable stage, the smaller the extreme value of compression rate, and the stronger the deformation resistance.
and bearing capacity. Under creep loading conditions, the maximum compression rate of the slurry is generally low, while the deformation resistance and bearing capacity are strong. The entire bearing process also shows three stages: rapid deformation, slow deformation, and stable deformation.

(2) The bleeding rate of the gangue slurry with a fluidity of 220–260 mm under a static state does not exceed 10%. However, after instantaneous and creep loading, more than 60% and 50% of the water passively leaks out of the slurry, respectively. The gangue particles in the slurry play the main bearing role. The compressive bleeding rate of the slurry has a threshold, and the entire bearing process can be divided into the supersaturated drainage stage, compressive bleeding stage, and no bleeding stage. The solid–water ratio of the compacted body after loading is mainly affected by the fluidity and loading mode.

(3) The self–bearing and deformation process of gangue slurry is manifested in three stages: the rapid compression and drainage stage, pore compaction and water bleeding stage, and particle crushing and elastic–plastic deformation stage. In the first stage, the slurry is rapidly discharged with supersaturated water, its deformation rate is fast, and the pore water is mainly subject to pressure. The deformation resistance and bearing capacity of the slurry are poor at this stage. In the second stage, the pores in the slurry are reduced due to the sliding backfilling of gangue and the crushing and compaction under the action of water wedges and dissolution, and the deformation resistance and bearing capacity of the slurry gradually increases. In the third stage, the slurry gradually forms a compacted solid with a stable solid–water ratio, and the gangue particles undergo elastic–plastic changes after being compressed, gradually transforming into a continuous medium. As a result, the bearing capacity is further strengthened, and the mechanical strength of the compacted body is affected.

(4) After creep loading, the compacted body undergoes the elastic stage, yield stage, reinforcement stage, and crushing stage during uniaxial compression, and the compressive strength of the compacted body with different fluidities under the 3 h creep loading reaches the maximum value. However, stress damage occurs after the 3 h loading. At the same time, the compressive strength of the compacted body of the 240 mm fluidity slurry under different loading schemes is the maximum, and the optimal scheme for the later mechanical strength of the backfilling material is obtained as a fluidity of 240 mm and creep loading of 3 h.

(5) In summary, for the mine with a mining depth of 800 m, when using the grouting backfilling process with a fluidity of 240 mm of gangue slurry, the maximum compression rates of the slurry are 45% and 47.7%, respectively, when the overlying rock strata collapse instantly and sink slowly. As the mining depth decreases, the pressure on the overlying rock decreases, and the compression rate of the slurry decreases, resulting in better control of overlying rock deformation.

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