Mechanical Response of Fractured Gangue Under Lateral Compression In Mined-Out Zones

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Abstract. This study investigates the compaction characteristics of fragmented gangue in residual mining areas, addressing stability challenges during upward mining of abandoned coal resources in China. Through confined compression tests using a WES-1000B electro-hydraulic servo testing machine, we examined the compaction behavior of in-situ sandy mudstone gangue under varying axial stresses (4-20 MPa) and moisture contents (0%-6%). The results reveal three distinct compaction phases: rapid densification (0-1.77 MPa), particle crushing and compaction (1.77-10 MPa), and stable compaction (10-20 MPa). Axial strain demonstrates logarithmic growth with increasing stress. Moisture content exhibits a nonlinear influence on compression deformation, with peak strain observed at 4% water content. The bulking factor decreases progressively with higher axial stress, reaching its minimum at 20 MPa axial stress and 4% moisture content. These findings elucidate the compaction mechanisms of fractured gangue and provide theoretical foundations for evaluating floor stability in upward mining of abandoned coal seams.

Keywords: broken gangue, axial stress, water content, coefficient of dilation

1 Introduction

In the process of coal resource development in China, due to the long-term use of non-scientific mining mode, especially the extensive production mode of "mining thick and abandoning thin, mining easy and difficult", the mining resource recovery rate is generally lower than 50%, and a large number of coal resources with mining value remain in the goaf[1]. According to incomplete statistics, the backlog of coal resources in the existing mined-out areas in the country exceeds 50 billion tons, equivalent to more than 15 times China's annual coal production, which not only causes serious waste of resources, but also causes a series of ecological and environmental problems such as surface subsidence and groundwater pollution. In this context, upward mining technology has become an important way to recover resources in the residual mining area. Through secondary mining above the goaf of the lower coal seam, this technology can effectively recover the coal resources left over by the traditional mining method, and it is expected

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that the overall recovery rate of the mine can be increased to more than 70%. However, the core problem of the implementation of this technology lies in the accurate evaluation of the stability of the overlying rock structure in the goaf, especially the analysis of the mechanical characteristics of the caving gangue compaction area[2-3]. Previous research results have shown that the stable state of gangue fill is affected by the synergistic effects of multiple parameters such as particle grading characteristics, water content conditions and compaction stress[4-6].

In gangue compaction mechanism studies, Chen Xiaoxiang[7] established a nonlinear mathematical model between permeability coefficient and compactness through crushed stone compaction tests; Liu Yongqiang's team[8] identified the characteristic three-stage evolution pattern in stress-strain curves of coal gangue backfill materials; while Zhang Tianjun et al.[9] used discrete element numerical simulation to demonstrate how discontinuous gradation affects compaction curves through particle breakage effects. Regarding deformation mechanisms, Liu Xiangfeng et al.[10] revealed the fragmentation-reorganization evolution of gangue particles via confined compression tests, finding that when fine particle (<5mm) content increases by 40%-60%, a new stress-transfer skeleton forms—providing microscopic evidence for staged deformation characteristics. Notably, while optimal moisture ranges for compaction have been confirmed in graded crushed stone and cement-stabilized aggregates[11], their applicability to fractured gangue systems remains unverified. Additionally, Xiao Meng[12] and Li Wei[13] systematically investigated the evolution of lateral pressure coefficients and acoustic emission characteristics respectively through confined compression tests, contributing essential experimental foundations for mesoscopic mechanism research. These studies collectively inform upward mining feasibility assessments but leave critical gaps regarding moisture-stress coupling effects on gangue's long-term compaction stability.

This study investigates the compaction characteristics of fractured gangue in residual mining areas under the combined effects of axial stress and moisture conditions[14], aiming to determine the critical state parameters for stable gangue compaction. The findings will provide theoretical support for upward mining feasibility assessment and the control of underlying coal seam floor stability, offering significant engineering value for improving coal resource recovery efficiency.

2 Experimental Materials And Methodology

2.1 Experimental Apparatus and Testing System

The confined compression tests on crushed gangue were conducted using a WES-1000B microcomputer-controlled electro-hydraulic servo universal testing machine, featuring a 1000 kN maximum loading capacity and real-time automated acquisition of load, displacement, and strain parameters. The custom-designed compression apparatus comprised three critical components: (1) a hardened alloy steel loading head, (2) a precision-machined confinement cylinder (Ø150 mm × 230 mm, fabricated from 13 mm thick seamless steel pipe), and (3) a rigid base platform. Structural calculations based on a safety factor of 1.5 and lateral pressure coefficient of 0.7 confirmed the system's

35 MPa axial stress capacity. Particle size distribution analysis pre- and post-compression was performed using standard sieve methods (ASTM D6913), with detailed apparatus configuration illustrated in Figure 1.

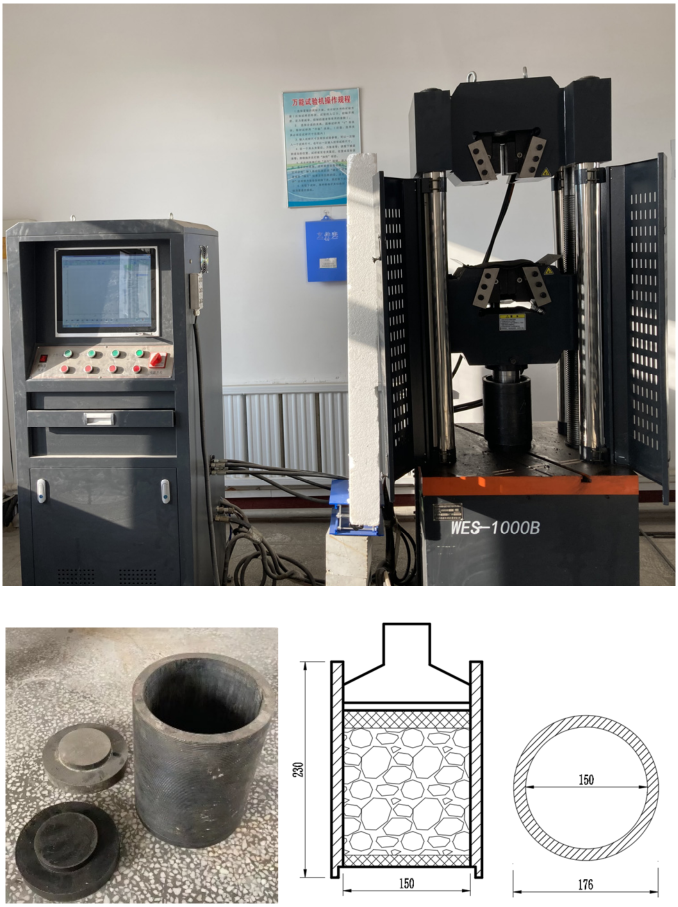

Fig. 1. Electrohydraulic servo universal testing machine and compression device diagram.

2.2 Experimental Materials

To accurately replicate the in-situ characteristics of fractured gangue, raw samples were collected directly from underground goaf areas and transported to the laboratory. The collected gangue was sieved into six distinct particle size fractions (0–5 mm, 5–10 mm, 10–15 mm, 15–20 mm, 20–30 mm, and 30–40 mm) using standard mesh screens (Figure 2). Each fraction was weighed to determine its mass proportion relative to the total natural gradation.

Based on the compaction cylinder dimensions, a total sample mass of 3,749 g was determined to achieve a 150 mm filling height. Sieve analysis of the raw gangue (0–50 mm) yielded the initial gradation distribution (Table 1), which was used to proportionally blend the six fractions. This process ensured the preparation of 20 uniformly mixed samples with identical initial gradation, maintaining consistency across all tests.

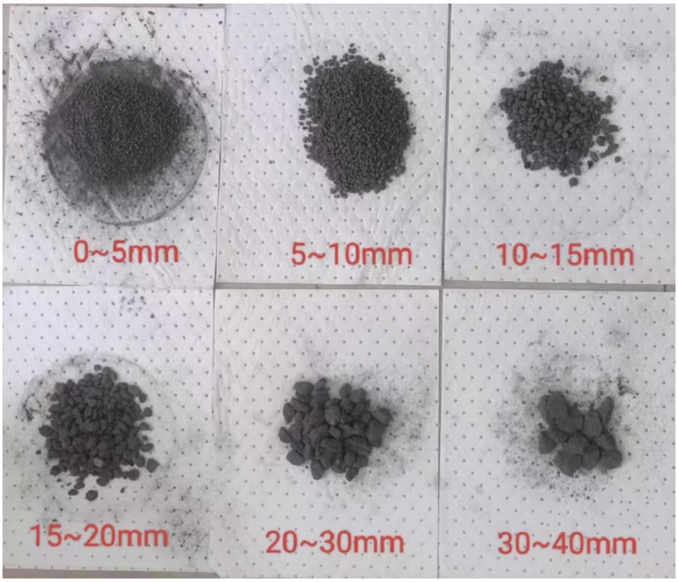

Fig. 2. Broken gangue materials with different particle sizes.

Table 1. Initial grading of crushed gangue samples.

Screen size /mm	Proportion of gradation	Mass /g
0~5	18.4	689.82
5~10	27.3	1023.47
10~15	21.6	809.78
15~20	17.2	644.83
20~30	9.3	348.66
30~40	6.2	232.44

2.3 Experimental Design

To investigate the coupled effects of axial stress and moisture content on the confined compression behavior of fractured gangue, a comprehensive experimental program was implemented. The study examined four distinct moisture conditions (0%, 2%, 4%, and 6% water content), with each group comprising five replicate specimens subjected to progressively increasing axial stresses (4, 8, 12, 16, and 20 MPa) through confined compression testing. Through the analysis of the law of compression deformation through the confined compression test, the mechanism of water content and axial stress in the compaction process of crushed gangue is obtained. The specific scheme is shown in Table 2.

Table 2. Crushing gangue side limit compression test scheme.

Group	Water Content (%)	Axial Stress Levels (MPa)
1	0	4, 8, 12, 16, 20
2	2	4, 8, 12, 16, 20
3	4	4, 8, 12, 16, 20
4	6	4, 8, 12, 16, 20

3 Study on Compression Deformation of Crushed Gangue in Residual Mining Area

3.1 Lateral Compressive Stress-Strain Relationship of Crushed Gangue

The test condition is confined compression, the compression device is rigid material, the lateral strain is very small and negligible, so it can be approximated that only axial strain occurs in the compression process of the sample. The axial strain of crushed gangue can be simply defined as the ratio of the axial deformation value at a certain time during the compression process to the initial loading height of the sample, and its calculation expression is shown in equation (1) :

$$\varepsilon = \frac{\Delta h}{h} \tag{1}$$

Where, ε is the axial strain of the crushed gangue sample, h is the initial loading height of the sample, mm, Δh is the axial deformation value at a time during the compression process, mm.

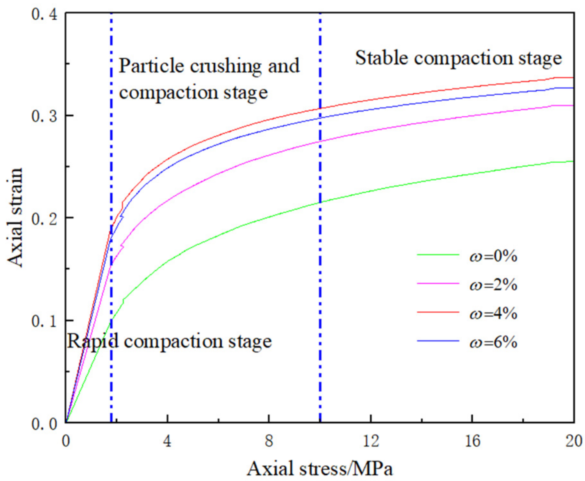

Fig. 3. Lateral compressive stress-strain curve of crushed gangue in goaf.

The electro-hydraulic servo universal testing machine automatically collected load and displacement data throughout the confined compression process of goaf crushed gangue specimens. After systematic analysis, the complete axial stress-strain curves (0-20 MPa loading process) under different moisture conditions were obtained, as presented in Figure 3.

The experimental results show that the axial strain of crushed gangue samples increases with the increase of stress in the process of confined compression under different water content, but the growth rate gradually decreases, and finally reaches the stable compaction state. By analyzing the stress-strain curve characteristics, the entire compression process can be divided into three typical stages:

Stage I (0-1.77MPa) : Rapid compaction stage. At this stage, gangue particles are in the initial loose accumulation state, and significant particle rearrangement and pore filling occur under the action of low stress, forming a preliminary skeleton structure. In this stage, large strain is generated under small stress increment, and the curve shows obvious zigzag fluctuation, which can be used as a sign of the end of this stage.

Stage II (1.77-10MPa) : particle crushing and compaction stage. With the increase of stress, the original particle skeleton structure begins to break down, and the displacement behaviors such as sliding and rolling occur among the particles, and some particles are broken twice. These broken particles further fill the structural pores, causing the strain growth rate to slow down, and the stress-strain curve presents typical nonlinear characteristics.

Stage III (10-20 MPa) : Stable compaction stage. At this stage, the gangue particles have completed the main structural restructuring and crushing process, and reached a higher degree of compaction. The residual porosity is very low, and only a small strain increment (about 2% of the previous strain) is generated during the subsequent stress increase, and the stress-strain relationship is approximately flat, indicating that the crushed gangue is gradually re-compacted and tends to be stable at this stage.

Relevant studies have shown that the logarithmic function ($\varepsilon = A\ln(\sigma + \mathrm{B}) + C$) can better describe the confined compression deformation characteristics of crushed gangue, and the model also has high fitting accuracy and applicability with the test data[15].

3.2 Analysis of Compressive Deformation of Crushed Gangue

(1) Analysis of the relationship between compression deformation and water content

The water content of crushed gangue is an important factor affecting its compression deformation. In order to compare and analyze the influence of water content on the lateral confined compression deformation of crushed gangue, the relationship curve between axial strain and water content of crushed gangue under different stresses was drawn, as shown in Figure 4.

The experimental data reveal that moisture content significantly regulates the compression characteristics of gangue, with axial strain initially increasing then decreasing as moisture rises, peaking at 4% water content. This phenomenon demonstrates water's dual mechanism on gangue compression: while moisture lubrication reduces interparticle friction and promotes deformation, water-filled pores simultaneously hinder particle rearrangement. Beyond the critical 4% moisture threshold, pore-filling effects dominate, causing strain reduction. This nonlinear relationship reflects water's complex influence on gangue's microstructure, where optimal moisture balances lubrication benefits against pore-space occupation, with 4% representing the equilibrium point for maximum compressibility before water's obstructive effects prevail in the granular matrix.

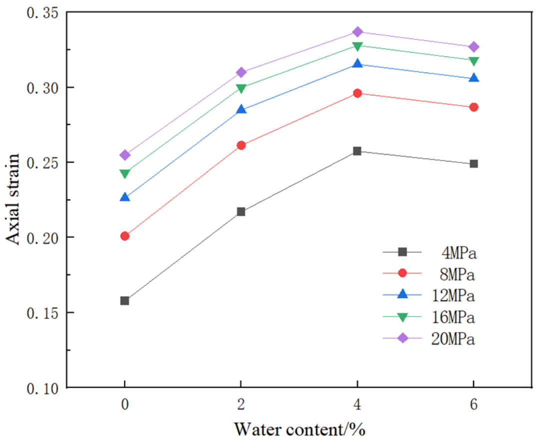

Fig. 4. Relationship between axial strain and water content.

(2) Analysis of the relationship between compressive deformation and axial stress

The degree of compressive deformation is a direct reflection of the compaction effect of crushed gangue. In order to further analyze the change of compressive deformation of crushed gangue at each stress stage, the relationship curve between axial strain increment and axial stress under different water conditions is drawn, as shown in Figure 5.

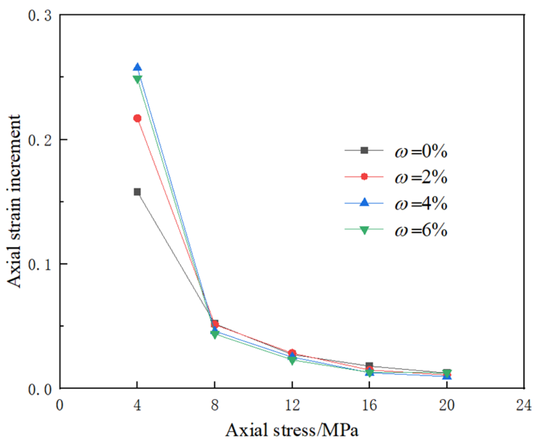

Fig. 5. Axial strain increment and axial stress relation curve.

Analysis of the experimental data in Figure 5 reveals distinct compression characteristics of the crushed gangue specimens: during initial loading (axial stress <4 MPa), the specimens exhibit rapid compression with high strain rates, indicating significant internal structural reorganization. As axial stress exceeds 4 MPa, the strain increment demonstrates pronounced nonlinear attenuation - at 8 MPa stress, the axial strain increment reduces to approximately 0.06, following a monotonically decreasing trend with increasing stress. When axial stress reaches 16-20 MPa, the strain increment decays below 0.02, marking the specimen's transition into a stable compression phase where axial strain progressively approaches a constant value, demonstrating the material's achievement of structural equilibrium under high confinement. This behavior reflects the complete transition from initial particle rearrangement through progressive fragmentation to ultimate densification.

3.3 Analysis of the Changing Law of the Compressional Expansion Coefficient of Crushed Gangue

The study reveals that the confined compression deformation of fractured gangue is closely related to particle gradation, composition, axial stress, and moisture content. To investigate the variation patterns of the bulking factor in roof-fractured gangue under different conditions in residual mining areas, the axial strain during compression was analyzed to characterize the bulking coefficient's evolution. As previously established, the initial filling height was 15 cm with a mass of 3749 g, and the in-situ gangue density was 2.376 g/cm³.

$$v_0 = \frac{m_0}{\rho} = \pi r^2 \cdot h_0 \tag{2}$$

Where, v_0 is the volume of rock before crushing, cm^3, ρ is the density of the rock before crushing, g/cm^3, m_0 is the initial loading mass of the steel drum, g, r is the inner radius of the steel drum, 7.5cm, h_0 is the initial height of the gangue before crushing, cm.

The initial height of gangue before crushing is obtained:

$$h_0 = \frac{m_0}{\pi r^2 \cdot \rho} \tag{3}$$

Due to the axial strain $\varepsilon = \Delta h / h$, the crushing coefficient can be characterized as:

$$K_P = \frac{h - \Delta h}{h_0} = \frac{h \cdot (1 - \varepsilon)}{h_0} \tag{4}$$

Therefore, the change curve of the crushing coefficient of crushed gangue samples from 0 loading to 20MPa under different water conditions was obtained by calculating the crushing coefficient with the above formula, as shown in Figure 6.

It can be seen from Figure 6 that under different water-containing states, the crushing coefficient of crushed gangue samples in the process of confined compression obviously decreases with the increase of stress, which is opposite to the change trend of axial strain. It can be found that the coefficient of crushing expansion of crushed gangue decreases from 1.68 to 1.32 in the compaction stage, with a decrease of 21.43%. The particle crushing and compaction stage decreased from 1.32 to 1.18 with a decrease of 10.61%; Finally, when the stable compaction state is reached, it decreases from 1.18 to 1.13, with a decrease of 4.23%. The change range of the crushing expansion coefficient in the whole process becomes smaller and smaller. When the reduction reaches about 4%, the compaction of crushed gangue tends to be stable.

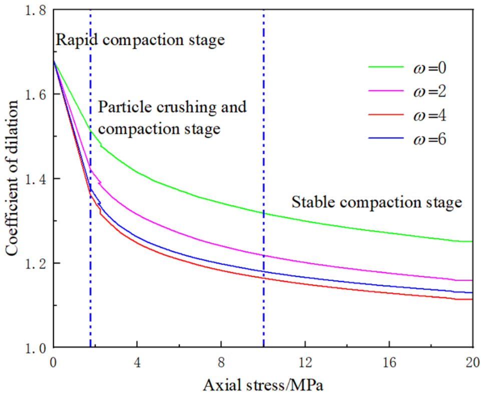

Fig. 6. Change curve of confining compression expansion coefficient of crushed gangue in goaf

At the same time, due to the joint influence of water content and axial stress, it can be found that the lateral compression deformation characteristics of crushed gangue show significant multi-factor coupling effect. A three-dimensional model of the crushing coefficient, axial stress and water content was established as shown in Figure 7.

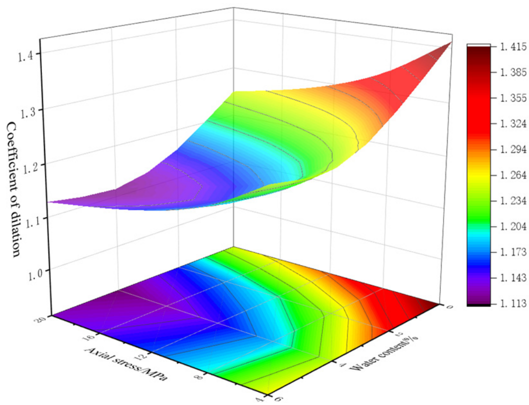

Fig. 7. Surface of relation between crushing coefficient and axial stress and water content.

Due to Figure 7 presents a three-dimensional response surface illustrating the relationship between bulking factor, axial stress and moisture content, exhibiting smooth elliptical paraboloid characteristics. Contour analysis reveals: (1) the bulking factor shows coupled dependence on both axial stress and moisture content, demonstrating an overall decreasing trend with increasing parameters; (2) an anomalous increase occurs within the 4%-6% moisture range, suggesting moisture-induced particle lubrication effects; (3) the minimum bulking factor (1.18) was measured at 4% moisture and 20MPa stress, providing theoretical support for stability optimization through moisture control in engineering practice. This quantitative model serves as a critical tool for evaluating both the compaction degree and stability of goaf gangue, enabling scientific assessment of whether floor stability in residual mining areas meets safety requirements for underlying coal seam extraction. The established correlations allow precise prediction of gangue behavior under various stress-moisture conditions, particularly for stability-sensitive applications in abandoned mine reclamation and safety control.

4 Conclusions

This study investigates the compaction characteristics of fractured gangue under varying axial stresses (4-20 MPa) and moisture contents (0%-6%) through confined compression tests, yielding the following key conclusions:

(1) The experimental results demonstrate that the confined compression process of fractured gangue progresses through three distinct phases: rapid compaction (0-1.77 MPa), particle fragmentation and compaction (1.77-10 MPa), and stable compaction (10-20 MPa). Axial strain follows logarithmic growth with increasing stress, with strain increments approaching 0.02 under high stress conditions (>16 MPa), indicating the material's transition to a stable compacted state. This 16 MPa threshold provides critical reference value for stability assessment in goaf areas, as it marks the stress level where gangue achieves structural equilibrium with minimal subsequent deformation, serving as an important engineering parameter for evaluating roof stability and settlement control in abandoned mine workings.

(2) The compressive deformation of crushed gangue is significantly affected by water content, and the axial strain increases first and then decreases with the increase of water content, reaching a peak value at 4% water content. When the content of water is low, it plays a lubricating role and promotes the slippage and recombination of particles. When the content is high (>4%), the pores are filled and further compaction is inhibited. The findings provide a theoretical basis for the gob drainage control and stability technology, and suggest that the water condition should be optimized to reduce the fluctuation of the crushing coefficient.

(3) The dilatancy coefficient decreases with the increase of axial stress and reaches the minimum value (about 1.2) when the stress is 20 MPa and the water content is 4%. The three-dimensional model shows that the axial stress is the dominant factor, but when the water content exceeds 4%, the compressive effect of the axial stress on the crushed gangue is inhibited. The research results can be used to evaluate the compacting

state of gangue in goaf, guide the stability control of coal floor in up-mining, and ensure the safety of mining in residual area.

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