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Study on the Mechanical Properties of Stone-Coal Composite under the Influence of Proportioning

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ABSTRACT

With the continuous advancement of backfill mining technology, the continuous mining and gangue backfilling technique has gradually become a key research focus in the field of coal mine backfill mining. By integrating continuous excavation technology with gangue backfilling processes, this approach effectively addresses environmental challenges such as surface subsidence and gangue accumulation. While achieving subsidence reduction and controlled emissions, it also facilitates the recovery of coal reserves trapped under buildings, water bodies, and railways, as well as irregular residual coal deposits, thereby resolving the dilemma of exhausted minable coal resources. However, current research on the synergistic bearing mechanisms between backfill bodies and coal pillars during the continuous mining and backfilling process remains limited. This paper investigates the failure characteristics of the "stone-coal" composite structure and conducts uniaxial compression experiments to analyze the mechanical properties and bearing capacity under varying cement ratios and gangue gradations. The results indicate that the stress-strain curves of the specimens can be divided into four stages: compaction, linear elasticity, plastic failure, and post-peak behavior. Compared to standalone coal samples, the compressive strength of the stone-coal composite is significantly enhanced. Unlike the stress-strain curve of pure coal pillars, no abrupt stress drop occurs in the post-failure stage, and the composite maintains certain residual support strength. This significantly mitigates the risk of sudden coal pillar collapse caused by stress concentration, thereby effectively protecting the coal pillars.

KEYWORDS

Continuous Mining Waste Rock Filling; Bearing Characteristics; Uniaxial Compression Test.

1. INTRODUCTION

Coal mining can induce surface subsidence and damage to the ecological environment [1-2]. Gangue backfill mining technology, developed to address challenges such as safe extraction of coal reserves under buildings, water bodies, and railways (referred to as "three-under" coal), coal gangue disposal, and land resource conservation, represents one of the green mining technologies in China. It has consistently served multiple functions, including the treatment of solid gangue waste, control of mining-induced subsidence, and environmental protection [3-5].

Currently, with the heightened national emphasis on ecological and environmental protection, the reduction of solid waste from mines and ecological rehabilitation have become increasingly stringent and urgent. Backfill mining aligns with the national strategy for ecological civilization and environmental sustainability[6-7], and its significant role has become increasingly prominent[1, 8].

The coal industry is a vital foundational sector tied to the national economic lifeline, underpinning sustained and sound economic development. In recent years, the application of efficient continuous mining techniques in China for recovering "three-under" coal and boundary coal resources has enabled high-yield and high-efficiency coal extraction. At Tianyu Coal Mine, through optimized layout of mining and backfill working faces and the adoption of continuous mining technology, coal resource recovery has been achieved using a simultaneous extraction-backfill operation model [9].

In line with specific geological and mining conditions, scholars have conducted in-depth research on overburden and surface deformation characteristics, ground pressure distribution, hazard control, and engineering applications of continuous mining technology. Innovatively, the strip Wongawilli mining method has been proposed, with extensive studies carried out on parameters such as underground roadway and excavation dimensions, working face configurations, elastic-plastic zones and stress states of coal pillars, and surface subsidence features [10-11]. These efforts have substantially advanced the development of continuous coal mining technology.

In recent years, to adapt to diverse geological and mining conditions, scholars have made improvements to backfill mining methods and technologies, proposing various enhanced approaches such as strip mining with gangue replacement extraction and short-wall gangue cemented backfilling. Zhang Jixiong, Tu Shihao, et al. [12-13] systematically summarized the overall framework of deep coal mine in-situ backfill technology and established an integrated mining mode combining underground gangue sorting with in-situ backfilling. Lu Bin et al. [14] introduced short-wall gangue cemented backfilling technology. Li Jian et al. [15] proposed the coal extraction technology using underground gangue backfilling without hoisting for mining coal reserves under embankments. Yin Wei et al. [16] developed a hybrid fully-mechanized mining technology combining pressure relief mining of protective strata with gangue backfilling and caving methods.

In the field of mechanical properties research on gangue-backfill composites: Numerous scholars have conducted extensive experimental investigations on mix proportion design, macro- and micro-scale physical-mechanical properties, and material stability of backfill materials. To determine strength parameters and failure characteristics of gangue-backfill composites, researchers have performed systematic mechanical tests under varying particle size distributions and confining pressures. Feng Guorui et al. [17] systematically investigated the effects of fine and coarse aggregates from waste concrete on the flowability and mechanical performance of backfill materials. Cao Shugang et al. [18] conducted compression tests on gangue masses under different gradations, reinforcement measures, and scale conditions, established their load-deformation behavior patterns, and developed a mechanical model for granular gangue bearing capacity. Guo Yuxia et al. [19] employed step-loading simulation methods to analyze and establish strength-time, wave velocity-strength, and creep constitutive models.

In summary, through the extensive application of backfill processes, scholars have optimized backfill technologies for specific conditions and conducted research on the mechanical properties of both backfill bodies and remnant coal pillars. These studies have provided theoretical and data support for backfill mining. However, there remains a scarcity of reported research on the mechanical properties and bearing capacity of the gangue-backfill and coal pillar composite under continuous mining and gangue backfilling conditions. The mechanical behavior and load-bearing capacity of this composite are critical for controlling overlying strata in continuous mining and backfill operations. Therefore, further investigation into the mechanical characteristics and bearing capacity of the gangue-backfill and coal pillar composite is essential.

2. RESEARCH ON THE BEARING FAILURE CHARACTERISTICS OF THE GANGUE-COAL COMPOSITE

In actual field operations, the relative connection methods between backfill lanes and branch lanes vary considerably, leading to different integration patterns between the gangue-backfill mass and the reserved coal at their junctions. The stress concentration zones of backfill lanes and branch lanes serve as stress concentration zones, which are often the most vulnerable to failure. Within these areas, the gangue-backfill mass and coal pillars perform distinct yet complementary functions, collectively maintaining the overall stability of the overlying strata and forming a coordinated gangue-backfill and coal pillar bearing system. Consequently, the load-bearing characteristics of the gangue-coal composite become a critical factor determining the effectiveness of surrounding rock control in continuous mining and backfill stopes. Investigating the mechanical response and failure characteristics under combined gangue-coal loading is of significant importance for identifying precursor failure signals in the composite structure and predicting its stability under varying conditions.

This chapter takes the gangue-coal composite structure as the research object and employs the RMT-150B rock mechanics test system to conduct comparative experiments on monolithic coal specimens, monolithic gangue specimens, and composite specimens with varying cement proportions (0%, 10%, 15%, 20%) and different gangue gradations (0-1mm, 1-5mm, 5-10mm, 10-15mm). The study aims to identify the optimal mix proportion scheme (cement content and gradation) for the composite specimens.

2.1. Sample preparation and processing plan

The experimental coal blocks used in this research were obtained from the Chaochuan Mine of Pingdingshan Tianan Coal Industry Co., Ltd. The constituent materials for the gangue-backfill mass were sourced locally to minimize backfilling costs, utilizing readily available resources. The mixture primarily consisted of coal gangue, P.O 42.5 ordinary Portland cement, sand, and water, with a solid content of 78% by mass. Based on the crushing ratio of the dual-rotor crusher employed at the continuous mining and gangue backfilling site in Chaochuan Coal Mine, the coal gangue was crushed and screened into five size fractions: 0–1 mm, 1–5 mm, 5–10 mm, 10–15 mm, and 5–15 mm.

2.1.1. Specimen Preparation

First, the coal gangue was crushed to below 15 mm using a jaw crusher and then screened through round-hole sieves with apertures of 1 mm, 5 mm, 10 mm, and 15 mm to obtain particles in five size ranges: 0–1 mm, 1–5 mm, 5–10 mm, 10–15 mm, and 5–15 mm. The coal gangue, sand, and cement were mixed according to the different proportions specified in Experiment 1 and Experiment 2 to form the specimens. After setting for 24 hours, the specimens were demolded and subsequently cured in a maintenance chamber at a temperature of 20°C and a relative humidity of 95%. Following 28 days of curing, the obtained gangue-backfill mass test blocks and experimental coal blocks were processed using a stone cutting machine, grinding machine, and wire cutter to prepare the final test specimens. The dimensions of the specimens are listed in Tables 2-1 and 2-2.

Table 2-1: Stone-Coal Combinations with Different Cement Ratios

Tailings gradation	matching	scaling	Cement proportion	quantity
Tailings gradation (<1mm: 1~5mm: 5~15mm =4:4:2)	12:7:1	1:1	5%	4
	6:3:1		10%	4
	11：6：3		15%	4
	11:5:4		20%	4
		sum		16

Table 2-2: Stone-coal composite with different gangue gradations

matching	Cement proportion	scaling	Tailings gradation	quantity
Scrap: fly ash: cement 11:5:4	20%	1:1	n=0.4	4
			n=0.5	4
			n=0.6	4
			n=0.7	4
	sum			16

Table 2-3: Ash particle size

		n=0.4		
grain size(mm)	0-1.0	1.0-5.0	5.0-10.0	10.0-15.0
mass fraction(%)	33.9	30.6	20.5	15
		n=0.5		
grain size(mm)	0-1.0	1.0-5.0	5.0-10.0	10.0-15.0
mass fraction (%)	25.8	31.9	23.9	18.4
		n=0.6		
grain size(mm)	0-1.0	1.0-5.0	5.0-10.0	10.0-15.0
mass fraction (%)	19.7	32.0	26.7	21.6
		n=0.7		
grain size(mm)	0-1.0	1.0-5.0	5.0-10.0	10.0-15.0
mass fraction (%)	15.0	31.3	29.0	24.7

During the processing of gangue-coal composite specimens, the gangue-backfill mass and experimental coal blocks were separately cut and bonded using marble adhesive. The specimens were divided into four groups based on shape and dimensions: vertically cut cubic specimens measuring 100×100×100 mm (length×width×height). The final specimens are shown in Figures 2-1 and 2-2.

Figure 2-1 Finished products of samples with different cement proportions

Figure 2-2 Finished products of samples with different gangue gradation

2.2. Test site for samples

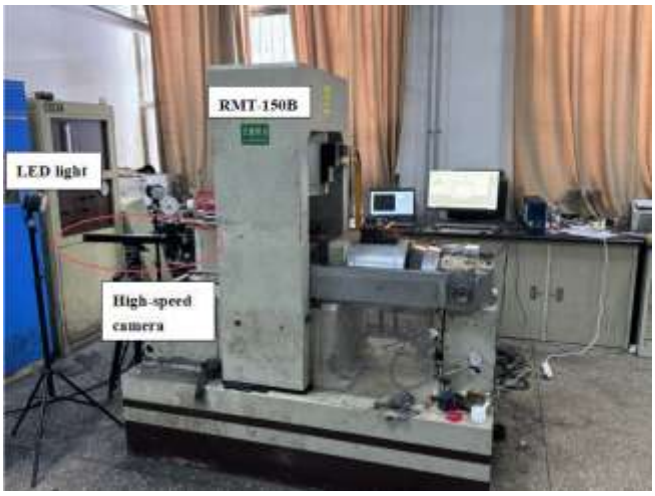


Figure 2-3 Single-axis compression test site

The experiment employed the RMT-150B rock mechanics test system to conduct conventional uniaxial compression tests on coal and gangue-backfill mass specimens with varying cement proportions and different gangue gradations. The mechanical testing protocol utilized displacement-controlled loading at a rate of 0.002 mm/s. A 1000 kN axial force sensor was used to measure vertical force, while a 50 mm axial displacement sensor monitored vertical deformation of the specimens.

2.3. Sample strength test

2.3.1. Specimen preparation and experimental scheme

The specimens required for the experiment were prepared and tested in accordance with the standards specified in the "Methods for Determining the Physical and Mechanical Properties of Coal and Rock". Initially, an RCD-250 core drilling machine was employed to extract cubic specimens measuring 100×100×100 mm (length×width×height). Four coal samples and four gangue-backfill mass specimens were prepared, as illustrated in Figure 2-4.

①coal sample ②Stone sample

Figure 2-4 Standard sample

The test employed the RMT-150B rock mechanics testing system to conduct conventional uniaxial compression tests on the prepared coal and gangue-backfill mass specimens. Displacement-controlled loading was applied at a rate of 0.005 mm/s. A vertical 100 kN force sensor measured the vertical force, while a vertical 5 mm travel sensor monitored the vertical deformation of the specimens. Two horizontal 2.5 mm displacement sensors were used to measure lateral deformation.

$$\text{axial stress: } \sigma = \frac{F}{A} \tag{2-1}$$

in the formula: σ——Rock uniaxial compressive strength (MPa);

F —— Load at specimen failure (N);

A —— Cross-sectional area of the specimen (mm²).

2.3.2. Test results

Based on the experimental results, the stress-strain curves of the monolithic coal specimens and monolithic gangue-backfill mass specimens are plotted in Figures 2-5 and 2-6, respectively.

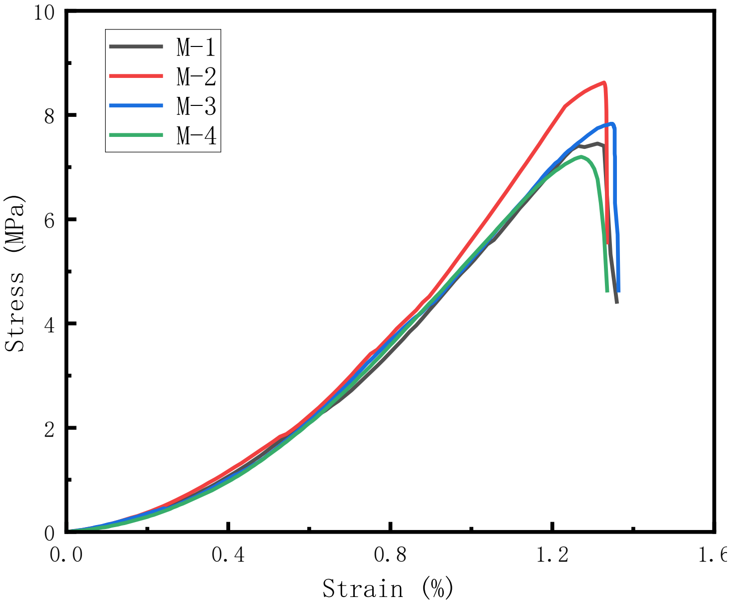


Figure 2-5 Stress-strain curve of coal monolith sample

As shown in Figure 2-5, the stress-strain curve of the monolithic coal specimen can be divided into four stages: In the first stage, the original pores within the specimen close under axial force, corresponding to an upward-bending segment of the stress-strain curve. The second stage is the elastic phase, characterized by a linear relationship in the curve. Upon entering the plastic stage, specimen fracture accelerates, with continuous generation of cracks, and the specimen volume transitions to expansion. Finally, as internal damage accumulates and cracks coalesce, the stress drops sharply, leading to specimen failure. Based on the uniaxial compression test results presented in Table 2-4, the average uniaxial compressive strength of the specimens is 7.78 MPa, the average elastic modulus reaches 7.09 GPa, and the average peak strain is 1.30%.

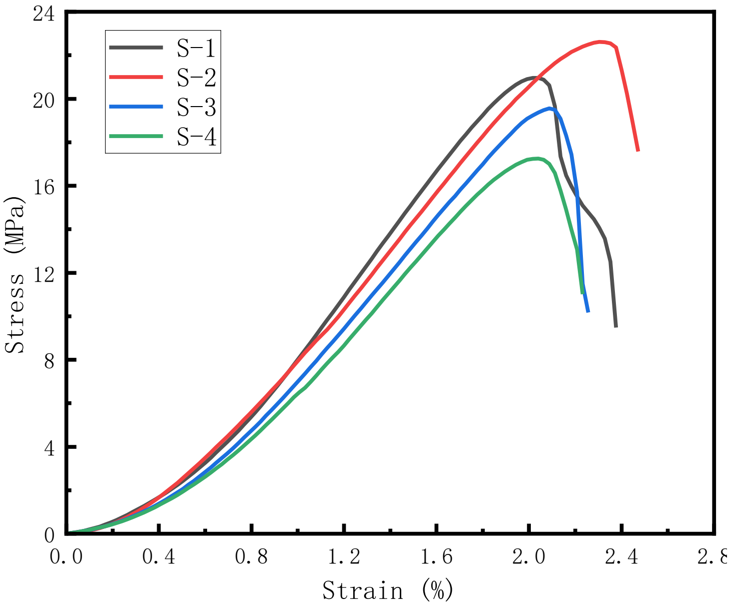


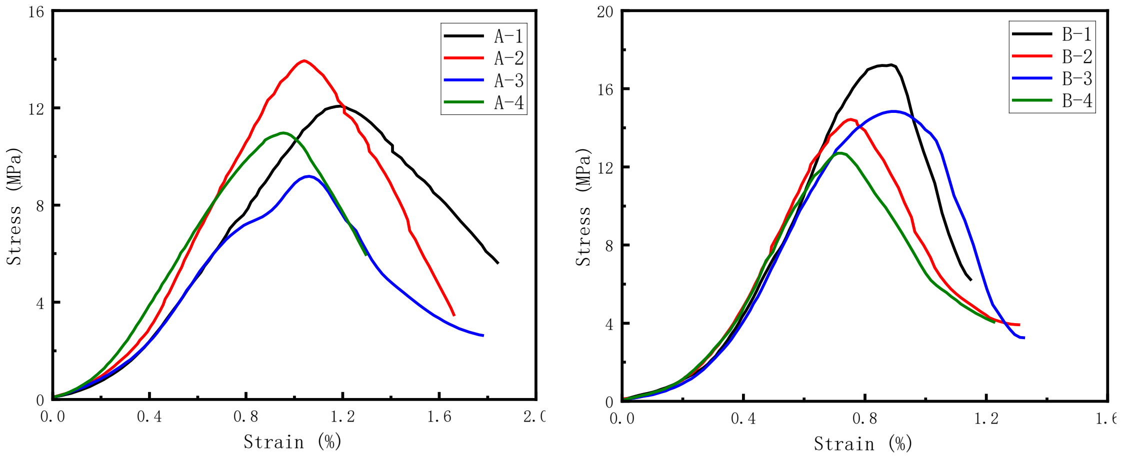
Figure 2-6 Stress-strain curve of monolithic specimen of rock mass

As shown in Figure 2-6, the stress-strain curve of the gangue-backfill mass specimen exhibits distinct differences compared to that of the coal specimen during the loading process. In the initial stage, internal voids within the specimen close under axial force, resulting in volume reduction. Subsequently, the specimen enters the elastic stage, characterized by a linearly increasing stress-strain relationship. With continued loading, micro-fractures in the gangue-backfill mass specimen accelerate, damage accumulates progressively, and the stress reaches its peak. In the post-peak stage, stress decreases while deformation continues to increase, exhibiting stress softening behavior. Nevertheless, the specimen maintains a certain residual support strength without undergoing an abrupt stress drop. According to the uniaxial compression test results in Table 2-4, the average uniaxial compressive strength of the specimens is 20.09 MPa, the average elastic modulus is 1.24 GPa, and the average peak strain reaches 2.11%.

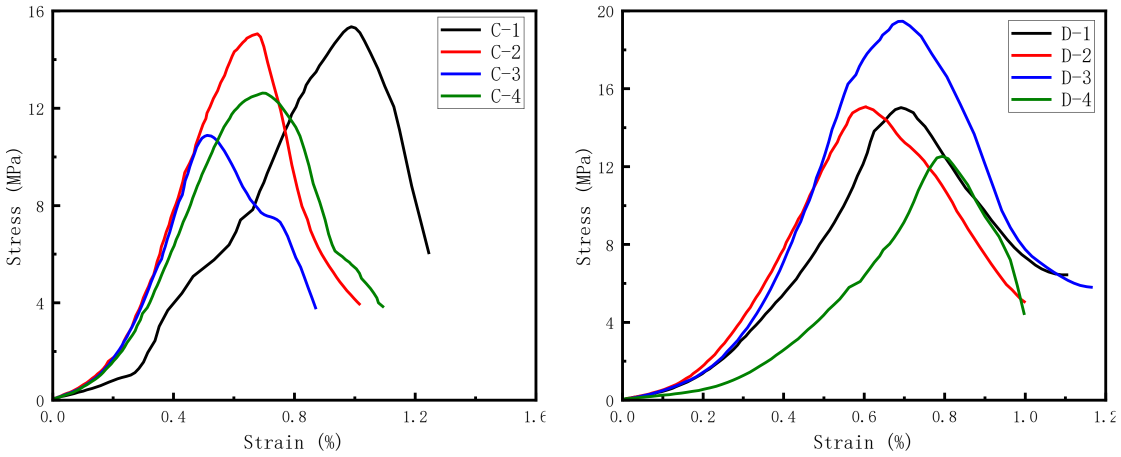
3. MECHANICAL PROPERTIES OF ROCK-COAL COMPOSITE BEARING

3.1. Uniaxial compression test of different cement mixtures

In this experimental group, consistency in gangue gradation was maintained while varying the cement proportions. A total of four experimental groups, designated as Group A, B, C, and D, were established, with four specimens in each group. The gangue gradation ratio was fixed at (<1 mm: 1–5 mm: 5–15 mm = 4: 4: 2). The mix proportions for each group were as follows:



Group A Group B



Group C Group D

Figure 3-1 Stress-strain curves of specimens with different cement ratios

Figure 3-1(A) shows the variation trend of the stress-strain curve for the gangue-coal composite with 5% cement content. As observed in the figure, the stress-strain curve exhibits typical characteristics of "initial compaction → linear elasticity → plastic yield → peak failure → post-peak attenuation," which align closely with the mechanical behavior of the gangue-coal composite. In the initial compaction stage: at very small strains (e.g., strain < 0.5%), the slope of the stress-strain curve is gentle, corresponding to the closure of internal micro-fissures and rearrangement of particles within the material, manifesting as "low stiffness and slow stress growth."

Figure 3-1(B) illustrates the variation trend of the stress-strain curve for the gangue-coal composite with 10% cement content. In the elastic stage: when strain < 0.4%, stress and strain exhibit a linear relationship, with the curve slope representing the elastic modulus of the material, reflecting its initial elastic deformation capacity. This indicates consistent deformation behavior among different specimens during the plastic stage, though differences exist in the post-peak softening rate (steepness of curve decline), reflecting variations in the speed of post-peak strength degradation.

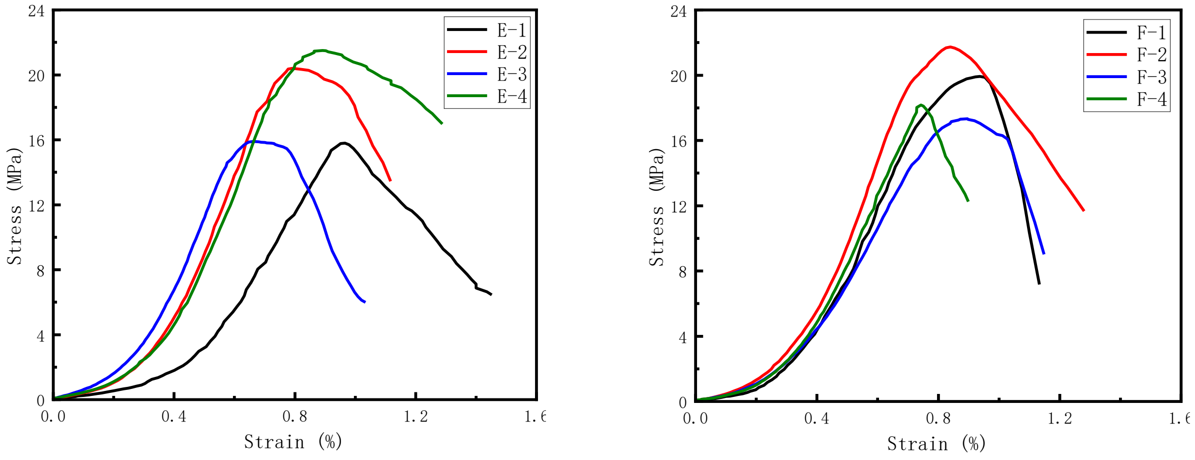
Figure 3-1(C) presents the variation trend of the stress-strain curve for the gangue-coal composite with 15% cement content. In the compaction stage (strain 0–0.2%): all curves rise gradually from the origin with increasing slopes, indicating progressive closure of initial internal fissures under compressive stress. When the gangue phase dominates load-bearing (C-1, C-2), the behavior demonstrates high stiffness, high peak strength, and low-strain brittle failure.

Figure 3-1(D) displays the variation trend of the stress-strain curve for the gangue-coal composite with 20% cement content. In the initial compaction stage: the stress-strain curve shows slight upward curvature, corresponding to the closure of initial micro-fissures under compression, exhibiting a nonlinear stress-strain relationship. In the linear elastic stage: the curve approximates a straight line, conforming to Hooke's law with a proportional linear relationship between stress and strain, indicating elastic deformation. During the plastic yield stage: the curve bends downward with significantly reduced stress growth rate, corresponding to the initiation of new micro-fissures and the material entering plastic deformation. In the post-peak failure stage: stress drops rapidly after reaching its peak, accompanied by macroscopic failure characterized by interconnected internal fissures and loss of load-bearing capacity.

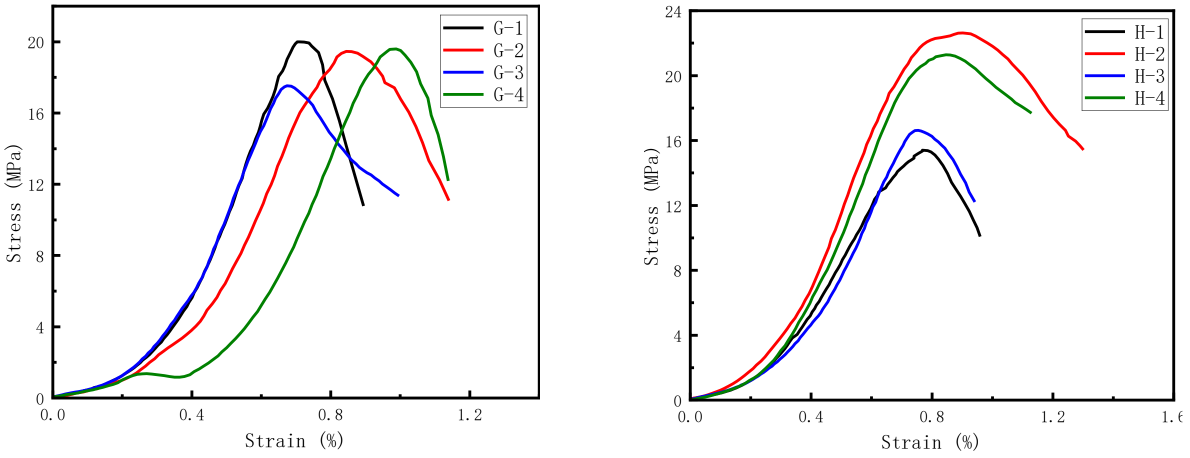
Based on the comprehensive analysis, as the cement proportion increases, the uniaxial compressive strength of the gangue-coal composite specimens gradually enhances. The highest peak stress is achieved at a 20% cement proportion, indicating significantly improved resistance to deformation at this ratio. Therefore, increasing the cement content effectively strengthens the load-bearing capacity of the gangue-coal composite.

3.2. Uniaxial compression test of different gangue gradation combinations

In this experimental group, the cement proportion was fixed at 20% while variations were made in the gangue gradation (i.e., the proportional distribution of different particle sizes). Four experimental groups, designated as Group E, F, G, and H, were established, with four specimens in each group. The mix ratio of gangue: fly ash : cement was maintained at 11: 5: 4 for all groups. The gradation parameters for each group were as follows:



Group E Group F



Group G Group H

Figure 3-2 Stress-strain curves of samples with different gangue gradations

Figure 3-2(E) shows the variation trend of the stress-strain curve for the gangue-coal composite with a gradation index of n=0.4. Analysis of the curve reveals: Stage 1 (Strain 0.0%-0.4%): Stress increases rapidly with strain, exhibiting a steep curve slope. This stage is dominated by the relative displacement of gangue blocks, where interparticle voids are quickly filled, macroscopically manifesting as "rigid compression" of the specimen. Stage 2 (Strain 0.4%-0.8%): The stress growth rate decelerates, accompanied by a reduced curve slope. This phase is characterized by fragmentation of gangue blocks and further filling of interparticle voids, macroscopically observed as "plastic compression" of the specimen. Stage 3 (Strain 0.8%-1.6%): Stress begins to decline, showing a "post-peak attenuation" pattern. This stage is governed by failure at particle interfaces and overall structural collapse of the specimen, macroscopically representing the "failure stage".

Figure 3-2 (F) illustrates the variation trend of the stress-strain curve for the gangue-coal composite with a gradation index of n=0.5.Initial Compaction Stage: At minimal strain, the stress-strain curve displays a slight concave shape, corresponding to the closure of internal micro-fissures and volumetric compression ($\varepsilon_v > 0$), accompanied by accumulation of elastic strain energy. Linear Elastic Stage: The stress-strain curve approximates a straight line, conforming to Hooke's law, indicating purely elastic material response without significant plastic deformation before the proportional limit. Plastic Yield Stage: The curve slope drops abruptly, and the volume transitions from compression to expansion ($\varepsilon_v < 0$), marking the yield limit where the material enters the plastic flow regime. Post-Peak Failure Stage: After reaching peak stress, the curve descends sharply, showing macroscopic rupture while retaining residual strength.

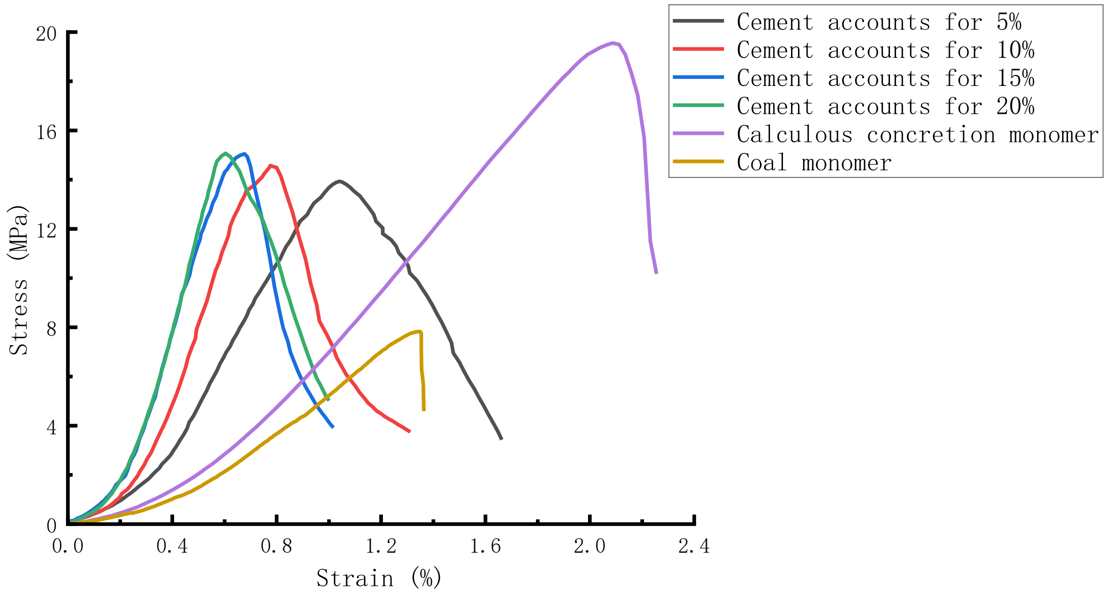


Figure 3-3 Stress-strain curves of cement-coal composite with varying cement proportions

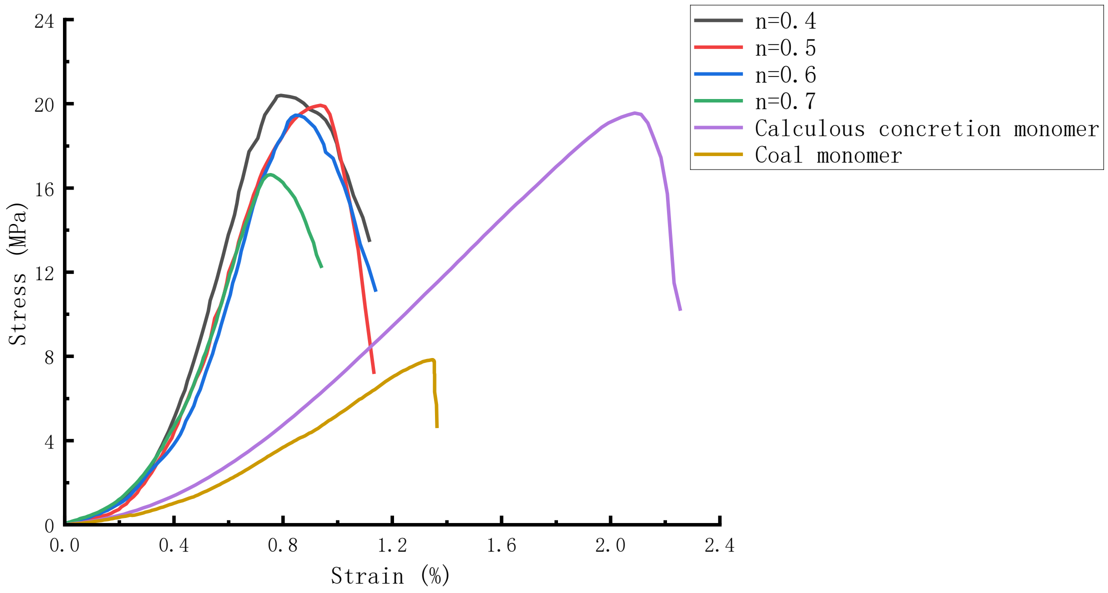


Figure 3-4 Stress-strain curves of coal-rock composite systems with different gangue gradation

As shown in the stress-strain curves of the gangue-backfill mass and coal pillar composite in Figures 3-3 and 3-4, the initial stage is characterized by rapid strain development as original pores gradually compact and close under loading. With increasing compressive stress, the coal pillar enters the elastic stage, exhibiting an approximately linear stress-strain relationship. As the load on the coal pillar progressively rises and compressive stress intensifies, the height difference between the gangue-backfill mass and coal pillar gradually diminishes. The curve shows significant increase in compressive strain, with the gangue-backfill mass undertaking load and forming a combined bearing system with the coal pillar.

In subsequent loading stages, the gangue-backfill mass demonstrates prominent load-bearing capacity and undergoes compressive deformation. Due to the distinct physical and mechanical properties of the two components, the gangue-coal composite exhibits significantly enhanced load-bearing capacity compared to monolithic coal specimens, with markedly improved synergistic load-bearing behavior between the gangue-backfill mass and coal pillar.

Unlike the stress-strain curve of a standalone coal pillar under compression, the gangue-coal composite shows no abrupt drop in compressive strength during the failure stage, maintaining considerable residual support strength. This substantially mitigates the risk of sudden coal pillar collapse caused by stress concentration, thereby effectively protecting the coal pillar.

In the present experiments, while the uniaxial compressive strength of composites with different cement proportions shows significant improvement compared to monolithic coal specimens, it remains lower than that of standalone gangue-backfill mass specimens. Conversely, composites with different gangue gradations (n=0.4, n=0.5, n=0.6) demonstrate substantial enhancement in uniaxial compressive strength, nearly matching that of standalone gangue-backfill mass specimens. Comparatively, the composites with optimized gangue gradation represent a more favorable proportioning strategy.

4. CONCLUSION

This chapter details the preparation and testing procedures for gangue-coal composite specimens with varying cement proportions (0%, 10%, 15%, 20%) and different gangue gradations (0-1mm, 1-5mm, 5-10mm, 10-15mm), along with monolithic coal specimens and monolithic gangue-backfill mass specimens. The experimental results from both test series for the gangue-coal composite specimens are analyzed.

(1) Two experimental schemes were implemented: Scheme 1 investigated different cement proportions (0%, 10%, 15%, 20%), while Scheme 2 examined different gangue gradations (0-1mm, 1-5mm, 5-10mm, 10-15mm). Eight experimental groups were established, each containing four gangue-coal composite specimens of different geometries. The testing process utilized the RMT-150B testing machine to record load and displacement data during uniaxial compression experiments, from which stress-strain curves were plotted.

(2) The stress-strain curves of the specimens can be divided into four stages: compaction, linear elastic deformation, plastic deformation, and post-peak failure. A cement proportion of 20% proved optimal in its group, yielding a uniaxial compressive strength of 15.50 MPa and an elastic modulus of 3.25 GPa. Compared to monolithic coal specimens, the average uniaxial compressive strengths of the four cement proportion variants increased by 48.59%, 90.75%, 73.26%, and 99.23%, respectively; while compared to monolithic gangue-backfill mass specimens, they decreased by 42.46%, 26.13%, 32.90%, and 22.85%, respectively. A gradation index of n=0.6 demonstrated optimal performance in its group, with a uniaxial compressive strength of 19.30 MPa and an elastic modulus of 4.44 GPa. Relative to monolithic coal specimens, the average uniaxial compressive strengths of the four gangue gradation variants increased by 136.76%, 147.81%, 148.07%, and 144.09%, respectively; while compared to monolithic gangue-backfill mass specimens, they decreased by 8.31%, 4.03%, 3.93%, and 5.48%, respectively.

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