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Compaction and Seepage Characteristics of Broken Coal-Rock Masses in Coal Mining: A Review of Laboratory Tests

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Abstract

Broken coal and rock (BCR) are an important component medium of the caving zone in the goaf (or gob), as well as the main filling material of fault fracture zone and collapse column. The compaction seepage characteristics of BCR directly affect the safe and efficient mining of coal mines. Thus, numerous laboratory studies have focused on the compaction seepage characteristics of BCR. This paper first outlines the engineering problems involved in the BCR during coal mining including the air leakage, the spontaneous combustion, the gas drainage, and the underground reservoirs in the goaf. Water inrush related to tectonics such as faults and collapse columns and surface subsidence related to coal gangue filling and mining also involve the compaction seepage characteristics of BCR. Based on the field problems of BCR, many attempts have been made to mimic field environments in laboratory tests. The experimental equipment (cavity size and shape, acoustic emission, CT, etc.) and experimental design for the BCR were firstly reviewed. The main objects of laboratory analysis can be divided into compression tests and seepage test. During the compaction test, the main research focuses on the bearing deformation characteristics (stress-strain curve), pore evolution characteristics, and re-crushing characteristics of BCR. The seepage test mainly uses gas or water as the main medium to study the evolution characteristics of permeability under different compaction stress conditions. In the laboratory tests, factors such as the type of coal and rock mass, particle size, particle shape, water pressure, temperature, and stress path are usually considered. The lateral compression test of BCR can be divided into three stages, including the self-adjustment stage, the broken stage, and the elastic stage or stable stage. At each stage, stress, deformation, porosity, energy, particle size and breakage rate all have their own characteristics. Seepage test regarding the water permeability experiment of BCR is actually belong to variable mass seepage. While the experimental test still focuses on the influence of stress on the pore structure of BCR in terms of gas permeability. Finally, future laboratory tests focus on the BCR related coal mining including scaling up, long term loading and water immersion, mining stress path matching were discussed.

Full Text

Preamble

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Review Article

Compaction and seepage characteristics of broken coal and rock masses in coal mining: A review in laboratory tests

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Keywords: Coal mining; Broken coal and rock; Laboratory test; Engineering problems; Experimental equipment; Breakage characteristics; Compaction characteristics; Seepage characteristics

Broken coal and rock (BCR) constitute a critical medium within the caving zone of goaf (or gob) and serve as the primary filling material in fault fracture zones and collapse columns. The compaction and seepage characteristics of BCR directly influence the safety and efficiency of coal mining operations, prompting numerous laboratory investigations into these properties. This review first outlines the key engineering problems associated with BCR during coal mining, including air leakage, spontaneous combustion, gas drainage, and underground reservoirs in goaf. Water inrush related to geological structures such as faults and collapse columns, as well as surface subsidence associated with coal gangue filling and mining, also involve the compaction-seepage behavior of BCR.

In response to these field challenges, researchers have developed various laboratory tests to simulate in-situ conditions. This paper reviews the experimental equipment (cavity dimensions and geometry, acoustic emission, CT scanning, etc.) and experimental designs employed for BCR testing. Laboratory analyses primarily focus on two categories: compression tests and seepage tests. During compaction tests, research emphasis is placed on bearing-deformation characteristics (stress-strain curves), pore evolution, and re-crushing behavior of BCR. Seepage tests primarily utilize gas or water as the medium to investigate permeability evolution under different compaction stress conditions. Experimental designs typically consider factors such as coal/rock type, particle size, particle shape, water pressure, temperature, and stress path.

The lateral compression test of BCR can be divided into three distinct stages: a self-adjustment stage, a breakage stage, and an elastic or stable stage. Each stage exhibits unique characteristics in terms of stress, deformation, porosity, energy, particle size, and breakage rate. Seepage tests concerning water permeability in BCR actually belong to variable-mass seepage, whereas gas permeability experiments still focus on how stress influences the pore structure of BCR. Finally, this paper discusses future directions for laboratory testing, including scaling-up considerations, long-term loading and water immersion effects, and matching mining-induced stress paths.

1. Introduction

Broken coal and rock (BCR) in coal mining refers to the fragmented coal and rock masses formed by mining activities or tectonic movement. BCR represents an important component medium in the caving zone of goaf and serves as the primary filling material in fault fracture zones and collapse columns (Zhang et al., 2019b; Liu et al., 2022b; Li et al., 2017a, 2019; Wang et al., 2017b; Cao et al., 2022). As coal is extracted from the panel, supports advance automatically and roof strata cave behind the face. The resulting caved zone is highly fragmented, typically extending upward three to six times the thickness of the mined coal seam. Caving induces relaxation of overlying strata characterized by mining-induced vertical and horizontal fractures and bedding plane separations (Fig. 1 [Figure 1: see original paper]). The caved zone and overlying fractured zone collectively form the "goaf (or gob)." Within the caving zone of goaf, large pore spaces accumulate substantial gas or water resources along with significant amounts of residual coal (Palchik, 2002; Zhang et al., 2016b). This condition affects safe production in adjacent working faces through hazards such as spontaneous combustion of residual coal, emission of toxic gases, and water inrush from goaf (Xiang et al., 2021; Tang et al., 2016; Zhang et al., 2021h; Ma et al., 2023; Niu et., 2022). However, residual coal, gas, and water resources in goaf also represent valuable resources (Hu et al., 2021; Feng et al., 2016). Furthermore, with the progressive development of abandoned mine reuse, the vast storage space in goaf, along with natural waterlogging areas, has led many abandoned mines to be repurposed as underground reservoirs and even pumped-storage power stations (Zhang et al., 2021b, 2021c, 2023; Pujades et al., 2016; Ordóñez et al., 2012). The influence of cyclic water storage and release under loading conditions on BCR pore structure has also become a focus of laboratory research. For BCR in faults and collapse columns, water inrush represents the primary concern, leading laboratory tests to focus on water seepage in BCR under loading (Cao et al., 2023; Ma et al., 2022; Zhang et al., 2021f). Gangue filling in goaf represents another coal mining-related problem involving the compaction characteristics of BCR (Wang et al., 2020a; Zhang et al., 2022b).

In summary, the compaction and seepage properties of BCR are crucial for safe mining and resource recovery in coal mines. However, because BCR in coal mines is typically in a closed state, its physical, mechanical, and seepage characteristics are difficult to detect directly (Zhang et al., 2020c, 2021e; Wang et al., 2020a). Consequently, laboratory tests on BCR serve as the primary research method for obtaining compaction and seepage characteristics and their influencing factors during coal mining. These tests also provide fundamental parameters for numerical simulation and theoretical models. With continuous advances in experimental monitoring technology and equipment, experimental monitoring parameters have become increasingly comprehensive, providing a foundation for mastering BCR compaction-seepage characteristics. This paper aims to review laboratory tests on broken coal and rock masses in coal mining. The review is organized as follows: Section 2 summarizes the engineering issues involving BCR during coal mining, illustrating corresponding experimental considerations for each issue. Section 3 discusses the current status of BCR experiments, including equipment, scheme design, and results analysis. Section 4 summarizes the compaction and seepage characteristics of BCR in laboratory tests, covering physical and mechanical properties (stress, porosity, particle size, breakage, energy) and porosity-permeability properties, along with reviewing BCR breakage mechanisms and criteria. Finally, Section 5 presents concluding remarks and future prospects.

2. Engineering Issues Related to Coal Mining Involving BCR

2.1 Issues Related to Faults and Collapse Columns

Mine water inrush represents a major geological disaster during coal mining, depending on critical factors including water sources, flow channels, water volume, and water pressure. Most water inrush events occur in anomalous geological bodies (e.g., collapse columns and faults) that provide primary channels for water inflow (Fig. 2 [Figure 2: see original paper]). As special geological structures with high permeability and poor compactness, rock strata near collapse columns and faults consist primarily of debris (Zhang and Tu, 2016; Zhang et al., 2021f). These structures create favorable conditions for water inrush, particularly under high water pressure and strong mining disturbances.

Under mining influence and water-rock interaction, the internal filling of broken rocks in collapse columns begins to erode, increasing porosity and permeability in faults or collapse columns. This activation of filling material inside collapse columns induces mine water inrush (Wang et al., 2020c; Zhang et al., 2016c; Zhao et al., 2022). When broken rock masses (such as argillaceous and siliceous materials) in collapse columns or faults cannot withstand mining-induced stress and/or hydraulic erosion conditions, mine water inrush occurs (Wang et al., 2014; Cao et al., 2022). It should be noted that faults and collapse columns not only cause water inrush but also affect roadway stability in coal mining, even when water is absent (Yan et al., 2023; Xing et al., 2018; Zhang and Tu, 2016). The stability of surrounding rock in broken zones of faults or collapse columns is poor, and water presence further weakens the rock mass, ultimately leading to roadway instability (Chen et al., 2023; Han et al., 2022a).

Water inrush in collapse columns and faults belongs to variable-mass seepage, a phenomenon that commonly exists in various rock and soil media and poses significant threats to engineering safety. Therefore, water-rock interaction during water inrush from faults and collapse columns primarily involves variable-mass seepage of broken rock mass. Critical factors in this process typically include water pressure, flow velocity, external stress environment, and porosity-lithology characteristics of the broken rock mass. For fault and collapse column broken zones affecting roadway stability, laboratory research primarily focuses on the cementation effects of grouting and other reinforcement measures. Critical factors in this process typically include slurry diffusion rate, slurry consolidation time, grouting pressure, slurry concentration, and slurry ratio.

2.2 Issues Related to Goaf

After coal seam mining, overlying strata can generally be divided into “three zones”: the caving zone, fractured zone, and bending zone from bottom to top, as shown in Fig. 2 (Cheng et al., 2017; Wang et al., 2017a; Liu et al., 2021b). The caving zone in goaf is generally composed of BCR, with porosity ranging from 30% to 45% according to laboratory measurements (Wang et al., 2020e; Zhang and Zhang, 2019). Due to high porosity and permeability in the caving zone, substantial pressure-relief gas and aquifer water resources flow into the goaf caving zone, creating both safety hazards and utilization opportunities. Therefore, coal mining problems in the goaf caving zone include two main aspects: disaster prevention and control (primarily spontaneous combustion of residual coal, gas and water emission, and impacts on upper and lower coal seam mining) and goaf resource utilization (such as residual gas extraction or using goaf pore space for water storage and purification).

2.2.1 Spontaneous Combustion of Residual Coal in Goaf In China, 60% of mine fires are caused by spontaneous combustion of goaf coal annually (Wang and Zhou, 2018). Frequent spontaneous combustion events in goaf areas have seriously affected safe coal mining. Research shows that spontaneous combustion of residual coal in goaf depends primarily on coal’s oxidation and heat release properties, air leakage and oxygen supply conditions, and heat storage environment (Onifade and Genc, 2020; Liang et al., 2019; Qiao et al., 2022). Based on spontaneous combustion risk levels, goaf can be divided into cooling zones, oxidation zones, and suffocation zones (Wu et al., 2011; Pan et al., 2013).

Numerical modeling results (Pan et al., 2013) have defined these zones as: 'cooling zone' (0–14 m from the face into goaf), 'oxidation zone' (14–86 m), and 'suffocation zone' (beyond 86 m), indicating different CO and O_2 behaviors in goaf, with the most significant spontaneous combustion risk occurring at the center of the oxidation zone due to heat accumulation and intense coal oxidation. Conventional models reveal that air leakage into goaf occurs mainly from the maingate, with goaf caving following an 'O-shaped' or 'annular-shaped' compaction trend (Zhang et al., 2019b; Guo et al., 2015). Typical gas distributions in conventional goaf gas models are shown in Fig. 3 [Figure 3: see original paper].

Considering spontaneous combustion conditions in goaf, mining or geological conditions with high residual coal content, severe air leakage, and high gas content are more likely to cause heating and spontaneous combustion of residual coal. For example, in fully mechanized top-coal caving mining, limitations in top-coal release rate result in large amounts of broken residual coal in goaf, making spontaneous combustion more likely (Cheng et al., 2016; Yang et al., 2021a; Deng et al., 2018). For shallowly buried coal seams, mining-induced fracture zones communicate with the surface, allowing oxygen-rich surface air to enter goaf through ground fractures and potentially cause spontaneous combustion of residual coal (Gao et al., 2020; Xu et al., 2011; Zhuo et al., 2018). High gas content in residual coal can further cause composite disasters of spontaneous combustion and gas in goaf (Xia et al., 2015; Zhang and Zou, 2022). Spontaneous combustion in goaf may trigger major accidents such as gas explosions (Xu et al., 2019; Lin et al., 2021).

Based on characteristics of coal spontaneous combustion and related prevention technologies, experimental research primarily involves changes in porosity and permeability of BCR in goaf caving zones under compaction stress conditions (Chu et al., 2017a,b; Li et al., 2019; Yang et al., 2021b). Meanwhile, the influence of temperature after coal spontaneous combustion and goaf water on BCR pore-permeability and compaction characteristics is also considered (Zhang et al., 2021g; Han et al., 2019, 2022b; Chu et al., 2017c; Chao et al., 2019; Yang et al., 2021b).

2.2.2 Gas Extraction in Goaf The main purposes of gas extraction in goaf include obtaining gas resources and reducing goaf gas content to ensure safe mining. Coal mine goaf contains abundant gas resources, particularly after coal seam mining. Extracting coalbed methane from abandoned mines has become an important coalbed methane resource (Karacan and Luxbacher, 2010; Meng et al., 2016, 2022; Yang et al., 2022; Qin et al., 2015; Feng et al., 2016). However, due to relatively low gas concentration in the goaf caving zone, current goaf gas extraction still aims primarily to prevent gas limit exceedance in working faces and prevent coupled disasters such as residual coal spontaneous combustion (Xiang et al., 2021; Qu et al., 2016). In gassy and spontaneous combustion-prone coal mines, goaf management is challenging for reducing gas explosion and spontaneous combustion risks to acceptable levels. Goaf gas drainage via vertical surface goafholes is a primary control method for managing gas emissions (Tang et al., 2016; Karacan, 2009; Hu et al., 2021; Juganda et al., 2020). However, gas extraction intensity requires careful control, as increased drainage capacity in high-gas mines may cause more air leakage in goaf, potentially increasing spontaneous combustion and gas explosion risks, as shown in Fig. 4 [Figure 4: see original paper]. This has been clearly explored in previous publications (Wang et al., 2022; Xiang et al., 2021), which focused on gas composition analysis of goaf drainage data and determining goaf atmosphere changes during dynamic longwall mining. Additionally, goaf gas extraction is commonly used in pressure-relief mining technology systems, primarily to extract pressure-relief gas from protected coal seams and prevent goaf gas from flowing into the protective seam working face (Yuan, 2009; Li et al., 2022b; Liu et al., 2022c; Zhang et al., 2015, 2017b).

Therefore, the comprehensive issue of goaf gas extraction focuses primarily on pore-permeability characteristics and their distribution in goaf during mining.

2.2.3 Stability of Goaf Roof and Floor and Surface Subsidence

Due to crushing and swelling characteristics of BCR in the caving zone, it plays a buffering role in roof pressure while also serving as the main medium for transmitting roof pressure to the floor, as shown in Fig. 5 [Figure 5: see original paper]. Thus, the bearing characteristics of BCR formed by rock fragmentation in gob roofs are important for ensuring roadway stability and relieving mine pressure (Liu et al., 2022a; Jiang et al., 2017; Huang et al., 2018; Shi et al., 2019).

The compaction process of the goaf caving zone can be divided into three stages during longwall face advancement: formation stage, gradual compaction stage, and stability stage. Different stages exhibit differences in roof bearing capacity (Zhang et al., 2016b, 2020b). During the gradual compaction stage, vertical stress on the caving zone increases exponentially with vertical strain, which can be calculated using the Salamon formula (Yavuz, 2004; Zhang et al., 2019b). For the floor, timely bearing of the caving zone helps compact the coal seam floor and prevent water inrush accidents from high-pressure floor aquifers. Therefore, to prevent floor water inrush, roof pre-fracturing is often performed to promote timely bearing of BCR in the caving zone (He et al., 2018; Pan et al., 2021; Liu et al., 2020c; Zou et al., 2022; Li et al., 2022a; Wang et al., 2020d).

Additionally, due to large pore space in the caving zone, long-term compaction deformation directly affects surface subsidence characteristics (Hu et al., 2022; Chen et al., 2022; Zhu et al., 2014). Theoretically, under long-term loading, BCR could be compacted to the original rock state, but in reality, broken rock cannot be compressed back to its original state, so broken rock mass creep behavior affects surface residual deformation (Palchik, 2015; Modeste et al., 2021; Cui et al., 2022). Another aspect involving surface subsidence and BCR in goaf is filling mining, particularly gangue filling mining, which requires studying the bearing-deformation characteristics of broken gangue (Zhang et al., 2019c, 2022c; Wang et al., 2020a; Liu, 2014). Therefore, experimental research on surface subsidence primarily involves stress-strain characteristics and long-term creep characteristics of BCR during compaction.

2.2.4 Underground Reservoir in Mine Goaf Using mine goaf to construct underground reservoirs has been proposed in recent years, with underground reservoirs employed to build pumped-storage power stations. These initiatives not only make full use of abandoned underground spaces but also promote environmental and ecological protection (Pujades et al., 2016; Zhang et al., 2021b; Menéndez et al., 2019; Fan et al., 2020). Coal pillar dams, residual coal pillars, and BCR (as shown in Fig. 6 [Figure 6: see original paper]) are the main bearing structures in goaf reservoirs, and BCR pore structure changes directly affect reservoir water storage capacity. In goaf reservoirs, BCR remains in a water-immersion and loading environment for extended periods. Circulating water storage and release from underground reservoirs can also affect BCR pore structure. Thus, laboratory tests on broken rock primarily include water immersion softening and seepage erosion, as shown in Fig. 6. Water softening effects typically involve the influence of immersion time or water content on BCR strength. The influence of water seepage is similar to variable-mass seepage in faults and collapse columns, as discussed in the mine water inrush section.

3. Laboratory Tests of BCR

Based on field problems involving BCR, numerous attempts have been made to mimic field environments in laboratory tests. Laboratory analyses primarily focus on two categories: compression tests and seepage tests. During compaction tests, research emphasis is placed on bearing-deformation characteristics (stress-strain curves), pore evolution characteristics, and re-crushing characteristics of BCR. Seepage tests mainly use gas or water as the medium to study permeability evolution characteristics under different compaction stress conditions. Throughout this research, factors such as coal/rock mass type, particle size, particle shape, water pressure, temperature, and stress path are typically considered.

3.1 Experimental Equipment

Experimental equipment selection primarily involves cavity size, shape, and loading conditions. Laboratory equipment size significantly impacts the upper particle size limit for BCR. According to rock and soil mechanics scaling principles, when broken coal samples are fragmented to dimensions less than 1/5 of the device diameter, boundary effects in laboratory tests can be alleviated (Zhang and Zhang, 2019; AASHTO, 2003). Table 1 lists the main experimental equipment currently used in laboratory research, showing two primary cavity types: cylindrical and square, with cylindrical shapes being predominant. Table 1 indicates that laboratory cavity diameters range from a minimum of 50 mm to a maximum of 400 mm, with 100–200 mm sizes being most common. Increasing cavity size expands the particle size range of fractured coal and rock masses but simultaneously reduces the upper limit of loading stress. Under the same pressure, the maximum stress in a 50 mm cavity is 64 times that in a 400 mm cavity. For rectangular cavities, laboratory-scale dimensions are similar to cylindrical cavities, with bottom dimensions around 100–200 mm per side. However, some particularly large rectangular cavity devices exceed conventional laboratory sizes; for example, Li et al. (2021a,b) used a 2600 × 1400 × 1600 mm simulation device for loading and unloading experiments on crushed gangue in goaf. However, such large devices cannot achieve high stress loading like small-scale experiments, so these large experimental setups primarily focus on similarity simulation, reducing stress through specific similarity ratios.

In addition to cavity size, experiments focusing on BCR seepage characteristics require equipment capable of conducting seepage tests. The testing medium is mainly gas (including methane and nitrogen) and water. During experiments, besides monitoring stress, displacement, and flow rate, other physical quantities are targeted and monitored according to experimental objectives. When studying variable-mass seepage, the amount of broken particles that seep out can be monitored. Acoustic emission monitoring equipment can characterize and locate breakage during loading (Feng et al., 2022; Li et al., 2023b). CT scanning can characterize pore structure during experiments (Tengattini et al., 2023). Additionally, temperature sensors, electrical resistance equipment, etc., are used for targeted research on temperature and resistance effects (He et al., 2021; Yang et al., 2021a,b). The main equipment and process for seepage and compaction testing of BCR are shown in Fig. 7 [Figure 7: see original paper].

3.2 Stress Path Design

Whether loading or seepage experiments, stress is the main factor affecting BCR porosity, breakage, and deformation. Therefore, stress path design during experiments is crucial. Table 1 shows that commonly used cavity loading involves lateral displacement loading, so in most cases only compaction stress is considered. During loading, the common method is constant displacement loading, such as 0.02 mm/min. This laterally constrained constant displacement loading method is primarily used to study BCR bearing and breakage capacity. In addition to lateral loading, some experiments set fixed axial pressure and confining pressure to study confining pressure effects. In this case, the loading method is usually servo loading, applying pressure according to stress magnitude. As laboratory research increasingly matches field engineering practices, more scholars are transforming actual stress paths into laboratory conditions. Zhang et al. (2019a,b,c,d) studied the effect of three loading-unloading cycles on broken coal sample permeability based on multiple loading-unloading impacts on goaf during coal seam mining. Li et al. (2021a,b) studied the effect of lateral cyclic loading on filling gangue bearing capacity under fixed axial pressure based on actual lateral cyclic loading of filling bodies during filling mining. To study bearing characteristics of coal gangue under long-term creep loading during filling mining, a load testing system for granular backfill materials was developed and creep compression tests were conducted under stepwise loading using waste rocks for backfill (Li et al., 2020c).

Therefore, more experimental studies are considering actual site stress conditions in loading design, but currently few compaction experiments consider actual stress paths in goaf. On one hand, monitoring compaction stress in goaf is not easy; on the other hand, field stress conditions are relatively complex and difficult to replicate in the laboratory. Since BCR in the caving zone is actually impacted by periodic roof collapse, further research should investigate the bearing and breakage characteristics of BCR in the caving zone under loading rate or impact conditions.

3.3 Sample Preparation and Particle Size Selection

BCR in goaf mainly includes coal measure rock layers, so research samples are primarily coal, sandstone, mudstone, limestone, and coal gangue, as shown in Table 1. During coal and rock sample preparation, materials are generally selected directly from goaf or drilled cores, then crushed and screened. Particle size affects BCR stress, porosity, and permeability, making reasonable BCR size selection necessary. Currently, two methods are commonly used for particle size selection: grouped particle size and mixed grading particle size (Table 1). The upper particle size limit is generally determined based on experimental equipment size, then experimental particle sizes are divided into several groups at certain intervals. This method mainly studies particle size effects on compaction or pore-permeability characteristics. Mixed particle size distribution primarily studies the influence of particle size gradation on BCR physical properties. The most commonly used grading model is the Talbot formula, listed in Eq. (1):

$$P = 100\left(\frac{d}{D}\right)^n$$

where P indicates the percentage of each particle size in the sample (%), D is the maximum particle size (mm), d is the current particle size (mm), and n is the Talbot index. When grading and particle size effects are not considered, equal proportions of each BCR group are often mixed. Due to laboratory equipment size limitations, BCR particle size rarely exceeds 100 mm, which is much smaller than actual goaf BCR particle sizes. Matching actual goaf BCR size is an important experimental issue. To address this, Zhang et al. (2022a) developed a goaf gradation model (GGM) based on fractal theory and roof-breaking characteristics of longwall mining to describe particle size distributions in caving zones. The model requires no fitting coefficients and relatively few parameters, facilitating its application. Furthermore, GGM can match gradation distributions at both engineering and laboratory scales, as shown in Fig. 8 [Figure 8:

see original paper].

Beyond particle size, BCR behavior and properties (e.g., shear strength, swelling, granular flow properties, and interfacial behaviors) are affected by particle shape, which influences contact orientation, porosity, and coordination number. However, controlling particle shape in the laboratory is not very practical, and experiments can only be conducted using 3D printing technology to manufacture artificial broken particles (Xu et al., 2022; Zhi et al., 2023).

3.4 Design of Flow Test

BCR seepage experiments primarily focus on gas extraction, air leakage, water inrush, and grouting reinforcement. Compared with BCR compaction experiments, seepage experiments must consider seepage parameters including medium, fluid velocity, or pressure. If studying gas extraction or air leakage in goaf, the seepage medium is generally gas, with nitrogen and methane being most common. Due to high permeability and low gas pressure in goaf, gas pressure change effects on seepage characteristics are rarely considered in experiments. For seepage experiments on water inrush from collapse columns and faults, the main seepage medium is water. In addition to monitoring flow rate, mass loss should also be monitored. Since water inrush involves water pressure influence, water pressure effects on seepage are also studied experimentally. In addition to stress path, seepage parameters, and coal-rock sample parameters, additional environmental factors must be designed for specific mining problems. In studying residual coal spontaneous combustion in goaf, temperature effects on BCR seepage and compaction characteristics are considered. When studying water storage capacity of underground reservoirs, BCR water saturation effects on compaction-seepage characteristics are considered, as shown in Table 1.

4.1 Particle Breakage Mechanism and Criterion

Various particle breakage criteria under simplified assumptions have been proposed and can be divided into two categories. The first category is stress criteria (Tsoungui et al., 1999; Ben-Nun and Einav, 2010; Esnault and Roux, 2013; McDowell and de Bono, 2013; Zhou et al., 2016; Wei et al., 2020), which set a threshold particle stress value; when particle stress exceeds this value, particles break. The second category is maximum contact force criteria (Åström and Hermann, 1998; Couroyer et al., 2000; Lobo-Guerrero and Vallejo, 2006; Marketos and Bolton, 2009; Elghezal et al., 2013; Ciantia et al., 2015), which set a threshold for maximum contact force between particles; when this force exceeds the threshold, particles break. Particle breakage is commonly attributed to local stress concentration resulting from maximum contact force (Clarke and Faber, 1987; O'Sullivan et al., 2017; Li et al., 2021b). Accordingly, some scholars employ maximum contact force as a breakage criterion. Maximum contact force criteria involve controlling grain crushing through one contact force, namely the maximum normal contact force. For 2D simulation, Lobo-Guerrero and Vallejo (2005a,b, 2006) assumed that when the number of contacts is three or fewer, particle stress conditions can be similar to those in a Brazilian disk test. Based on this assumption, they utilized tensile stress (σ_t) as a breakage judgment condition. Ciantia et al. (2015) adopted the failure limit condition, $k_{mob} \geq k$, as the breakage criterion for 3D DEM simulation. When calculated flow strength exceeds particle intrinsic strength, particles break. In a lateral consolidation test, Cil and Buscarnera (2016) explored the influence of three different force criteria based on three size-effect formulas for particle characteristic strength, examining their impact on macro- and micro-mechanical behavior of particle aggregates.

The concept of particle crushing stress is introduced based on the homogenization principle, which assumes uniform internal stress distribution when particles are subjected to stress. Various stress criteria have been proposed, including mean stress, octahedral shear stress, and von Mises stress. In a 2D case, Åström and Herrmann (1998) used a mean stress criterion, assuming any force affects the average stress tensor of particles with radius R:

$$\sigma_{ij} = \frac{1}{V_p} \sum_c n_i^{(c)} F_j^{(c)}$$

where n_c is the number of contacts on the particle, $n_i^{(c)}$ is the component of the unit normal vector at contact point (c) in direction i, $F_j^{(c)}$ is the contact force in direction j, and V_p is particle volume. Tsoungui et al. (1999) simplified particle stress conditions into two components: hydrostatic pressure and deviatoric stress state, as depicted in Fig. 9 [Figure 9: see original paper]. They utilized the 2D Drucker-Prager criterion to determine particle breakage. Similarly, Ben-Nun and Einav (2008) derived the equivalent force tensor (Eq. (4)) as the criterion. It is worth noting that the particle breakage criterion remains the characteristic strength of particles.

$$S_{ij} = \frac{1}{L} \sum_c P_1^{(c)} n_i^{(c)} n_j^{(c)}$$

where P_1 is the contact force, L is unit length, and D is the disc diameter.

The impact of coordination number on particle breakage has been a significant research area. Ben-Nun and Einav (2008, 2010) expanded previous work by considering coordination number influence in force determination criteria, moving beyond the assumption that particles only break when coordination number is less than or equal to 3. Russell and Wood (2009) proposed an analytical formula for maximum flow shear strength of spherical particles under radial loading, found applicable to particles with contact numbers between 6 and 12 in particle aggregates (Russell et al., 2009). Given the critical role of coordination number in particle breakage, this paper delves deeper into its influence. The maximum contact force threshold can be determined by an expression of flow shear strength. Using this approach, Ciantia et al. (2015) and Cil and

Alshibli (2016) set three stress thresholds based on different size-effect formulas for particle characteristic strength.

Particle behavior in an assembly is complex; particles can be subjected to high hydrostatic pressure and low deviatoric stress under multiple contact forces (high coordination number). These conditions make particle breakage determination using average stress difficult. To address this, several criteria have been proposed. McDowell and Bolton (1998) suggested using octahedral shear stress as a breakage criterion, with characteristic tensile stress from single particle crushing tests as the threshold. Zhou et al. (2014) adopted the Mohr-Coulomb criterion with truncation as the breakage criterion. Yang et al. (2015) defined fracture criteria for tensile and shear failure. Cil and Buscarnera (2016) still used the octahedral shear stress criterion proposed by McDowell and de Bono (2013) and set strength size effects.

Additionally, breakage initiation, evolution, and attenuation can be determined by the maximum dissipation principle using thermomechanics and micromechanics. Breakage extent can be quantified by changes in maximum particle size, size polydispersity, and fractal dimension of the gradation (Shen et al., 2019; Hanley et al., 2015).

4.2 Physical and Mechanical Properties

Traditional lateral compression stress-strain curves can be divided into three stages: self-adjustment stage, breakage stage, and elastic or stable stage. At each stage, stress, deformation, porosity, particle size, energy, and breakage rate exhibit distinct characteristics. This section discusses BCR compaction characteristics in these three lateral compression stages.

4.2.1 Stress and Porosity Evolution Characteristics

During experiments, stress and displacement can be monitored directly, but BCR porosity and breakage rate must be calculated. BCR porosity is the ratio of void volume to total sample volume, commonly characterized using the volumetric method:

$$\phi = 1 - \frac{V_s}{V_b}$$

where V_s is solid volume and V_b is sample volume. Sample volume can be determined by dividing sample mass by its density. In addition to the volumetric method, the strain method can also be used for porosity calculation, which is actually consistent with the volumetric method.

With monitoring technology development, CT technology has gradually been applied to BCR loading experiments, enabling real-time porosity evolution characterization during loading. Fig. 10 [Figure 10: see original paper] shows pore evolution during BCR mixture loading. As axial stress increases, porosity gradually decreases, especially in the upper space of the broken sample, indicating that BCR compacts gradually from top to bottom during lateral compaction. Based on three-dimensional pore space reconstruction, porosity can be calculated under different stress states. Fig. 10f shows porosity loss during loading. With increasing axial stress, porosity decreased from 58.9% initially to 20.3% at 14 MPa, resulting in 28.6% loss, with the porosity decrease rate gradually diminishing.

Fig. 11 [Figure 11: see original paper] shows typical evolution laws of stress-strain, acoustic emission, porosity, and other factors during BCR compaction in three stages. In the self-adjustment stage, BCR adjusts its arrangement by overcoming friction resistance with assistance from gravity and limited compaction pressure. At this stage, only a small amount of BCR breakage occurs to achieve a relatively stable compaction state. Porosity reduction mainly comes from structural adjustment and limited rock mass deformation, as shown in Fig. 11. Stress at this stage is very small and increases slowly. Due to low stress, coal and rock mass breakage rate is limited, as is porosity reduction.

In the breakage stage, BCR breaks again when compaction stress exceeds BCR breaking strength. At this stage, new void structures form due to BCR re-breakage, while small particles begin filling pore spaces formed by large BCR, causing significant porosity decrease, as shown in Fig. 11b. Due to continuous re-breakage, stress shows fluctuating increase, and BCR secant modulus gradually increases. Macroscopically, the stress-strain curve at this stage can be expressed by Eq. (6) (Zhang et al., 2019b; Salamon, 1991):

$$\sigma_c = E_0 \frac{\varepsilon}{\varepsilon_m} \left(1 - \frac{\varepsilon}{\varepsilon_m}\right)^{-1}$$

where E_0 is initial elastic modulus, σ_c is compaction stress, and ε and ε_m are vertical strain and maximum vertical strain, respectively. ε_m is the critical strain between the breakage stage and subsequent elastic stage; when strain exceeds ε_m, re-breakage barely occurs. At this stage, due to large-scale BCR fragmentation, acoustic emission counts begin to increase significantly, as shown in Fig. 11c. Acoustic emission can also perform breakage localization; Feng et al. (2022) proposed an AE location method for broken porous media, finding that particle re-breaking first occurs in the middle layer and gradually moves toward upper and lower layers as compression increases (Li et al., 2023b). When strain exceeds ε_m, breakage rarely occurs due to decreased particle size and increased coordination number. At this stage, vertical stress increases linearly with strain, meaning BCR behaves like an elastic material (Zhang et al., 2022b). Porosity decrease is minimal, mainly originating from BCR deformation, as shown in Fig. 11.

4.2.2 Particle Size and Breakage Rate Evolution Characteristics

Particle size distribution during BCR compaction directly affects mechanical and seepage properties. However, most research on compacted BCR particle size distribution focuses on fractal and grading characteristics after crushing, with insufficient research on particle size distribution during experiments. Loading method and initial particle size distribution are the main factors affecting particle size distribution characteristics before and after experiments. Zhang and Li (2017), Han et al. (2017), and Kong et al. (2019) separately calculated rockfill material particle size distribution and gradation changes under cyclic loading. Combined with acoustic emission devices, Feng et al. (2022) provided particle size distribution and spatial layer distribution after particle breakage. Yang et al. (2017) used a coal gangue sorting system to provide particle size distribution at different impact velocities. Wang et al. (2020b) measured grading curves and particle size distribution of gangue with different Talbot indices before and after crushing.

Fractal dimension can quantify particle size distribution and predict its evolution characteristics. Yu et al. (2018) conducted particle size fractal research under different grading, axial stress, and loading rates, analyzing particle size distribution evolution in different lithologies and providing the fractal dimension (D) growth trend with axial stress as Eq. (7):

$$D = 0.55e^{-0.55\sigma_c} + 4.0908\sigma_c + 2.5382$$

Chen et al. (2021a,b) integrated grading experimental data from Fu et al. (2009) and fitted the functional relationship between fractal dimension limit increment value ΔD_u and initial fractal dimension D_0:

$$\Delta D_u = 1.2 + 0.6D_0$$

Yu et al. (2022) believe that Weibull distribution is suitable for describing breakage characteristics in early compaction stages, while fractal distribution is suitable for later stages. Zhang et al. (2018c, 2020a) found that fractal dimension gradually increases with axial stress, environmental humidity, and creep time, and decreases with immersion time.

Measuring particle size distribution also enables calculation of sample breakage rate, an important parameter during BCR loading. Traditional breakage rate calculation can be performed through grading curves, taking the area enclosed by pre- and post-loading grading curves as breakage amount, then dividing by defined breakage potential to obtain breakage rate. Hardin and Blandford (1989) used the area enclosed by particle size $d = 0.074$ mm and the initial grading curve as breakage potential. Einav (2007) believes there is a limit grading for particle breakage, so theoretically it is more reasonable to remove the $d = 0.074$ mm limit and instead use the area enclosed by initial and limit grading curves as crushing potential. The initial grading curve, tested grading curve, and area enclosed by the maximum particle size line $d = d_{max}$ are represented as S_0, S_1, and S_2 (Fig. 12 [Figure 12: see original paper]), respectively. The breakage rate index can be expressed as:

$$B_r = \frac{S_1 - S_0}{S_2 - S_0}$$

In addition to particle grading, particle fractal dimension is used to calculate breakage rate. Chen et al. (2021) revised breakage rate calculation for initial fractal dimension > 2.6 based on the Hardin model:

$$B_r = \frac{\sigma_3/p_a(4b-1)}{(a+b\sigma_3/p_a)(4-D_0)} - \frac{\sigma_3}{p_a}$$

where a and b are fitting parameters, σ_3 is confining stress, D_0 is initial fractal dimension, and p_a is atmospheric pressure. Han et al. (2017) introduced fractal dimension change to define particle breakage rate:

$$D_m = D_r - D_0$$

where D_0 and D_r are fractal dimensions of particle size distribution before and after testing, respectively. D_m is the particle breakage rate expressed by fractal dimension.

Due to difficulty achieving real-time grading measurement during loading, and even with CT scanning, identifying particle size during loading is challenging, making it difficult to obtain breakage rate development during BCR loading. Therefore, current methods describe sample breakage rate after loading. Zhang et al. (2021d) measured gradation during loading by removing samples at different stresses, but this method has obvious defects: repeated BCR removal destroys their structure, impacting subsequent loading and breakage. Another method uses multiple sample sets (with consistent initial grading) to test grading under different stresses, obtaining breakage rates under different stress conditions (Yu et al., 2020). However, different samples cannot achieve consistency in breakage evolution during loading.

4.2.3 Energy Evolution Characteristics

Energy evolution analysis is often based on loading stress or acoustic emission. Particle breakage refers to the process of converting work done by load into surface energy of new broken particles. Work done by load is mainly consumed by friction, rolling, crushing, and recombination between particles (Indraratna and Salim, 2002; Ueng and Chen, 2000). Two common methods express energy during BCR compaction. One uses energy conservation and stress-strain relationships to derive energy conversion relationships, as shown in Fig. 13 [Figure

13: see original paper]. Assuming no thermal energy conversion during compaction, work done by the compaction device on BCR can be regarded as the sum of energy dissipated and released during compaction (Li et al., 2019; Li et al., 2017a,b,c). Dissipated energy (U_d) during compaction can be expressed as:

$$U_d = \int_0^{\varepsilon_a} \sigma_c d\varepsilon - \int_0^{\varepsilon_b} \sigma_c d\varepsilon - \lambda\mu \frac{D}{4H} \int_0^{\varepsilon_a} \sigma_c d\varepsilon$$

where ε_a is strain corresponding to compaction stress σ_c, ε_b is residual strain after unloading, λ is lateral pressure coefficient, μ is friction coefficient between cavity and BCR, D is cavity diameter, H is initial BCR loading height, and U is work done by the compaction device on BCR. Experiments show that regardless of size, elastic energy and dissipated energy increase with stress, and sample particle size significantly affects its elastic and dissipated energy (Li et al., 2017b).

Another method adds AE devices during experiments, utilizing the AE system's energy monitoring function to derive real-time energy changes and accumulated energy during compaction, as shown in Fig. 11c (Xin et al., 2020).

Particle breakage is accompanied by energy evolution. The relationship between plastic work and particle breakage was established by linking particle breakage with energy, proposing a functional relationship between breakage energy and particle breakage rate. As discussed by Lade et al. (1996), the relationship between particle breakage rate and plastic work satisfies a hyperbolic function. Liu et al. (2014) argue that exponential functions better reflect the relationship between energy and breakage rate. Jia et al. (2017), Hu et al. (2018), Gao and Ye (2023), and Guo and Chen (2022) used energy to characterize particle breakage in triaxial tests, finding that plastic work increases gradually with crushing degree, fitting the relationship between plastic work (W) and BCR breakage rate in triaxial tests using hyperbolic curves as:

$$W = \frac{aB_r}{1 - bB_r}$$

In addition to plastic work, Russell (2011) introduced redistribution energy of broken particles to explain particle rearrangement. Wang and Arson (2018) argue that redistribution energy of broken particles also includes plastic dissipation energy, suggesting that energy dissipation due to load redistribution is significantly greater than that due to surface creation.

4.2.4 Influencing Factors for Physical and Mechanical Properties

Main factors affecting parameter evolution (stress, porosity, breakage) during compaction include particle size, coal/rock mass strength, and others. Larger sample strength results in longer self-adjustment stages and greater compaction stress for the same strain. Rock strength is negatively correlated with residual swelling coefficient, porosity, and compaction (Chen et al., 2014). BCR size significantly affects breakage model and rate. Breakage evolution characteristics depend on three main factors: stress, sample strength, and coordination number, all related to sample size (Zhang et al., 2021d). In the elastic stage, BCR with large particle size have more coordination numbers, resulting in lower breakage rates than small particle size BCR. For single BCR, larger sample size results in lower strength, causing easier breakage at initial loading with the same coordination numbers. Thus, porosity loss rate decreases with increasing strength and increases with particle size, regardless of coal-rock mixing type (Li et al., 2023a). For residual coal spontaneous combustion, smaller coal particle size results in larger specific surface area and stronger adsorption capacity of coal and oxygen molecules, leading to larger oxygen consumption rate (Jia et al., 2022; Xu et al., 2021; Onifade and Genc, 2020).

In addition to strength and particle size, BCR temperature and moisture content affect its strength, further influencing compaction characteristics. Both water and high temperatures reduce coal strength, making breakage easier (Chu et al., 2017b; Su et al., 2012). Loading method also significantly affects BCR breakage and porosity changes. Zhang et al. (2017a) measured that during unloading, only porosity loss caused by BCR deformation can be restored. Li et al. (2020a,b,c) compared BCR compaction characteristics at different loading rates and counted AE counts during loading, showing that AE count increases with loading rate. Zhang et al. (2020a,b,c,d) compared and analyzed fractal characteristics of crushed coal-rock mass under different environmental humidity, creep time, and axial pressure, showing that deformation and damage degree increased with all three factors.

4.3 Porosity and Permeability Properties

BCR pore-permeability research focuses on gas migration and extraction, spontaneous combustion in goaf, and water inrush from faults and collapse columns. Therefore, gas and water are primarily used as seepage media during experiments.

4.3.1 Gas Permeability

Due to relatively high porosity and low gas pressure of BCR in goaf, little research exists on gas pressure effects on gas seepage. Thus, experimental tests still focus on stress effects on BCR pore structure in terms of gas permeability. Therefore, pore structure evolution is basically consistent with compaction experiments that do not consider seepage. Zhang et al. (2019a,b,c,d) used CH_4 as the seepage medium, finding that broken rock sample permeability was greater than broken coal sample permeability, and that initial permeability and initial fracture compression rate increased logarithmically with particle size. Li et al. (2019) also showed that smaller particle size resulted in smaller permeability. Pang et al. (2021) studied osmotic characteristics of broken coal, finding Reynolds numbers distributed between 1230 and 2207. Zhang et al. (2020a,b,c,d) established a formula for the relationship between permeability, porosity, and fractal dimension. Yu et al. (2020) found that permeability can be fitted to a quadratic polynomial function of relative fragmentation rate. In addition, besides lateral compression, confining pressure is also considered in many permeability studies. Zhang and Zhang (2019) used triaxial loading and unloading to study BCR permeability evolution, providing a permeability formula considering particle size. Considering impacts of spontaneous combustion or water accumulation in goaf on gas permeability, Chao et al. (2019) found that temperature, water content, and pore pressure reduce permeability. Chao et al. (2021) obtained the effect of axial stress on coal spontaneous combustion by combining gas flow rate, oxidizing gas derivatives, oxygen consumption rate, heat release intensity, apparent activation energy, and other parameters, finding that increased axial stress first promoted then suppressed broken coal spontaneous combustion. In summary, different compaction degrees in residual coal in goaf caused by different stresses lead to different porosities and permeabilities, which significantly impact spontaneous combustion occurrence (Li et al., 2018; Chu et al., 2017a,b,c; Li et al., 2019; Ma et al., 2016b; Jin et al., 2015).

4.3.2 Water Permeability

Unlike gas permeability testing, water permeability tests also consider water pressure effects on seepage, primarily because water pressure is an important factor for water inrush. Meanwhile, water seepage drag force is much greater than gas drag force, and larger flow velocity creates greater drag force, significantly impacting BCR pore evolution. Therefore, water permeability experiments on BCR actually belong to variable-mass seepage. With continuous erosion seepage development, small materials are continuously lost, causing rapid permeability increase and even inrush disasters. Liu et al. (2018) designed a triaxial variable-mass seepage test system, studying water pressure and initial porosity effects on erosion characteristics. They observed water flow state transition from Darcy to non-Darcy flow and proposed critical water inrush conditions. The quantity of particles lost from samples first increased then decreased with increasing flow velocity (Wang et al., 2021). Ma et al. (2016) used Reynolds number calculation and the relationship curve between pore pressure gradient and seepage velocity to show that broken gangue permeability characteristics belong to non-Darcy flow. Ma et al. (2019) divided the seepage process into four stages: growth period, stationary period, decline period, and stagnation period. Liu et al. (2021a,b) established modified models of permeability and inertial drag coefficient, finding that permeability and inertial resistance coefficient shape factor have good power function relationships with particle size. CT images indicated that fine particle erosion in broken samples is obviously non-homogeneous, leading to seepage channel formation and uneven pore throat distribution (Zhou et al., 2022). The above research mainly focuses on stress or water environment effects on BCR seepage, with little consideration of initial

BCR structure effects on water seepage. Based on this, Wang et al. (2014), Kong and Wang (2018), Yu et al. (2018), and Zhang et al. (2019a) investigated permeability and porosity variation laws with flow pressure considering collapse column filler grading composition, external water pressure, filling material, and rock block cementation. Feng et al. (2018) and Wu et al. (2019) studied Talbot index n effects on hydraulic force, particle mass loss, porosity, and permeability, dividing the penetration process into three stages where porosity, mass loss, and mass loss rate were negatively correlated with n.

5.1 Coal Mining Issues

This paper summarizes the main engineering backgrounds for BCR experiments, including air leakage related to BCR in goaf, spontaneous combustion of residual coal, gas drainage, surface subsidence, underground reservoirs, and water inrush related to geological structures such as faults and collapse columns. It also includes issues related to coal gangue filling and mining. The above issues primarily focus on physical-mechanical characteristics and pore-seepage evolution during BCR compaction in goaf. Research on rock pressure, surface subsidence, and backfill mining mainly focuses on deformation and bearing characteristics during BCR loading. For air leakage, spontaneous combustion, and gas extraction in goaf, the main focus is gas seepage characteristics of BCR under load conditions. For water inrush from faults and collapse columns and underground reservoirs, research focuses on pore changes under loaded and water seepage conditions. With continuous coal resource exploitation, numerous abandoned mines have been formed, and reuse of closed mines has become an important consideration for subsequent goaf management. Problems encountered during abandoned mine reuse mainly include creep characteristics of BCR in goaf during long-term loading, weakening effects under long-term water immersion, and sedimentation of broken rock masses in goaf. Meanwhile, impacts of engineering disturbances on BCR in goaf must be considered, such as ground building loads and vehicle loads. Sometimes, grouting into the goaf caving zone is necessary, requiring further research on grout flow, diffusion, and consolidation in BCR.

5.2 Experimental Equipment and Design

Currently, two main types of goaf experiments exist: BCR compaction experiments and BCR compaction-seepage experiments. In both types, cavity size is a concern that directly affects maximum particle size and loading methods. The commonly used cavity shape is cylindrical, with rectangular cavities being relatively rare. Cavity diameter is mainly concentrated between 100 and 200 mm. The loading method during experiments is primarily lateral compression. Displacement loading is mainly used when studying compaction and breakage characteristics, while stress loading is mainly used when studying seepage characteristics. Matching between loading stress path design and actual mining stress path is relatively low, currently only considering loading-unloading effects. There are three BCR particle size design methods: (1) grouping by particle size,

(2) designing according to distribution functions such as the Talbot function, and (3) attempting to match actual site particle size distribution, such as the fractal-based GGM model.

During seepage experiments, the seepage medium is mainly divided into gas and water. For gas, the focus is on the goaf caving zone with high porosity, so pressure is generally set low and constant. For water seepage, the current focus is on studying critical values for water inrush from BCR caused by faults and collapse columns, requiring investigation of water pressure change effects on pores. In terms of monitoring and characterizing experimental results, equipment such as CT and acoustic emission enables characterization of stress, displacement, porosity, permeability, and breakage characteristics.

Therefore, current experimental design is increasingly matched with site engineering problems, with more monitoring and consideration factors. However, the following factors should also be considered: (1) Experimental stress path design can match actual goaf stress paths. Currently, reports exist on measured compaction stress in goaf (Zhang et al., 2021e; Chen et al., 2021a,b), but these have not been incorporated into experiments. (2) The main BCR loading method is lateral compression, with little consideration of triaxial stress effects, mainly because BCR experiences large deformation under load, making true triaxial corners difficult to handle. Traditional triaxial loading may cause excessive stress and damage to rubber sleeves. (3) Due to equipment size limitations, BCR size design differs significantly from actual site rock mass size. The scaling effect of mechanical and flow properties of BCR should be studied. (4) Time factors have received little consideration in BCR experimental research. With abandoned mine reuse becoming a hot topic, changes in mechanical and seepage properties under long-term (years or even decades) compaction and water immersion can be further studied. Meanwhile, water-rock interaction impacts on water quality in broken rock masses can also be further investigated. (5) While CT can achieve real-time scanning of pore structure during BCR loading, obtaining particle size distribution changes during loading is difficult. Therefore, currently only pre- and post-loading grading changes can be obtained to calculate breakage rate. Acoustic emission counting can characterize breakage during loading, so using AE counts during loading to calculate breakage rate could be considered.

5.3 Compaction and Seepage Characteristics of BCR in Laboratory Test

The lateral compression test of BCR can be divided into three stages: self-adjustment stage, breakage stage, and elastic or stable stage. At each stage, stress, deformation, porosity, and breakage rate exhibit distinct characteristics. Breakage characteristics of broken rock granules are the main reasons for stress, porosity, and breakage rate changes across these three stages. Both particle size (grading) and rock strength affect BCR compaction characteristics. Temperature and moisture content of broken rock mass affect its strength, further influencing BCR compaction characteristics. Water permeability experiments on BCR actually belong to variable-mass seepage, while gas permeability experiments still focus on stress effects on BCR pore structure.

Future work should include longer-term compaction experiments to observe BCR residual deformation under compaction stress over time. The particle size range of BCR in compaction tests should be further extended, and the recrushing and rearrangement mechanism of BCR during flow compaction tests and its effect on permeability should be researched. There are relatively few experiments on grouting reinforcement of BCR, especially for water-filled faults or collapsed column broken zones. Thus, competitive flow tests considering multiple seepage media (slurry, water, gas, etc.) deserve attention. Moreover, more attention should be paid to applying laboratory-scale results to engineering-scale problems. Some qualitative conclusions need to be transformed into quantitative models applicable to field-scale models. In addition, immersion time factors are limited to short durations in laboratory tests (usually less than half a year); however, rock mechanical parameters weaken under long-term water immersion (more than several years), and pore structure evolution should receive more attention. Besides, the influence of water immersion on strength degradation of broken rock mass can be further studied.

Data availability statement: Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement: Cun Zhang: Conceptualization, Writing – original draft. Yanhong Chen: Data curation, Writing – original draft. Zhaopeng Ren: Data curation, Formal analysis. Fangtian Wang: Writing – review & editing.

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Note: Figure translations are in progress. See original paper for figures.

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