Experimental Investigations on Mechanical Properties of Consolidated Samples for Collapse Columns under Seepage-Stress Coupling Effects

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Triaxial seepage tests were conducted on the consolidated collapse column specimens to investigate their mechanical properties under seepage-stress coupling effects using a triaxial multifield coupled mechanical test system for rocks. The effects of initial consolidation pressures and specimen components on mechanical properties and seepage characteristics of consolidated collapse column specimens were analyzed. Test results showed the following: (1) The stress–strain curves of consolidated collapse column specimens could be classified in three stages, namely, compaction stage, linear deformation stage, and creep-like deformation stage, while the permeability during loading showed an obvious four-stage evolution of gradual decrease, stable development, rapid increase, and slow decrease. (2) Under same sample components, the permeability characteristics of consolidated collapse column specimens showed an obvious initial consolidation pressure effect. The initial consolidation pressure changed the distribution of pores and fractures in the specimens, leading to a decreased peak permeability as the initial consolidation pressure increased. (3) At the initial stage of loading, the permeability of consolidated specimens was mainly affected by the initial consolidation pressure, and the corresponding permeability decreased with the increase of the consolidation pressure. When the consolidated specimens were gradually compacted, the main factor influencing the permeability changed to the specimen components. The peak permeability of consolidated specimens comprising grey mudstone and conglomerate was the largest, while the fuchsia mudstone would reduce the specimen permeability, and the peak permeability decreased with the fuchsia mudstone components.

1. Introduction

Karstic collapse columns are a special kind of hidden vertical structure, and they are typically developed in Carboniferous Permian coalfields in northern China. The karstic collapse column is generally composed of fractured rock and gap-filling materials, which are consolidated under the complex geological processes and the in situ stresses [1, 2]. In recent years, with an increase of mining depth in China, the karstic collapse column is easily connected with the Ordovician limestone aquifer and the failure zone of coal seam floor to form the vertical water inrush channel under the influence of mining [3]. Consequently, Ordovician limestone water floods into the working face through the water inrush channel, causing significant casualties and huge economic losses, and these has become a huge hidden danger affecting the safety of mining in China. Therefore, it is of great practical significance to investigate the seepage characteristics of karstic collapse columns for the prediction and prevention of water damage in coal mines [4, 5].

Numerous scholars have contributed to the investigations of seepage characteristics of Karstic collapse columns, which are important to understand the water inrush mechanism of karstic collapse column during mining excavation. Using the FLAC3D software, Wang et al. investigated the failure processes of karstic collapse columns under different conditions.
conditions, and the stress, strain, and deformation in the plastic zones of karstic collapse columns and their surrounding rocks were also studied [6]. According to the fluid-structure coupling theory and strength criterion, Qu et al. proposed a method to embed the fluid-structure coupling relationship of fractured rock mass into the FLAC\textsuperscript{3D} internal flow mode, and the effects of mining pressure and plastic damage on the variations of pore water pressure and seepage field for karstic collapse column were analyzed [7]. Song et al. used the complex function and the elastic-plastic mechanics to derive the critical equation of the water inrush mode for the “thick walled cylinder” mechanical model of karstic collapse columns with elliptical sections, and the analytical solution of the stress distribution of the collapse column was verified using finite-element software [8]. Bai et al. established a mechanical model for the description of the seepage behavior of coal seam floor containing the karstic collapse column, and the seepage relationship between the karstic collapse column and the surrounding rocks was explained. Zhang et al. studied the seepage stability of cemented fractured coal rock under triaxial pressures and tested its permeability and non-Darcy coefficient. In addition, the seepage instability evolution criterion was calculated using the non-Darcy seepage equation [9–11]. Using the the MTS815.02 system and self-designed water flow device, Ma et al. investigated the effects of particle grading on compaction and seepage characteristics of a granular mixture of crushed limestone from karstic collapse columns [12, 13]. Research results showed that the effective porosity, particle crushing characteristics, and seepage characteristics of the crushed limestone were not only related to the degree of compaction and the particle size of the mixture but also to the arrangement and initial pore structure. Zhang et al. analyzed the effects of the consolidation pressure, initial moisture content, and confining pressure on the permeability of the filling materials in the karstic collapse column [14, 15]. It was found that the permeability coefficient of collapse column fillings decreases with an increase of the consolidation pressure and a decrease of the initial moisture content. It was revealed that changes in the seepage through fillings are indeed caused by porosity changes, and there is a power function relationship between the permeability and porosity. Yu et al. studied the seepage characteristics of collapse column fillings with different initial porosities and cementation strength values using high water pressure and high water flow using a self-designed seepage testing system [16]. The mass loss and mass gain were compared to explore the variation mechanism of seepage characteristics. Wang et al. and Xu et al. conducted different permeability tests on sandstone with different confining pressures and pore water pressure values to study the relationship between permeability coefficient and volumetric strain during deformation and the correspondence between effective confining pressure and peak failure strength [17, 18]. The above research results have positively impacted the understanding of the water inrush mechanisms in collapse columns [19, 20].

Gaps between fractured rock mass inside the collapse column are filled, and cementation occurs under long-term complex geological processes. Thus, most of the fully developed collapse columns are impervious. The stress-seepage coupling under mining influences makes the deformation and stability analysis of well-cemented collapse columns more complicated [21–23]. In particular, it is more important to analyze the seepage characteristics of consolidated structure consisting the fractured rock and gap-filling materials within the collapse columns. Therefore, the study of seepage characteristics of consolidated collapse column samples in the full stress–strain process are more conducive to the in-depth understanding of the seepage and water inrush law of collapse columns. In this study, sample materials of collapse columns were collected from the field and then consolidated and remolded. The strength and permeability of consolidated collapse column samples were measured by the steady-state method using a triaxial multifield coupling mechanical test system. The influences of different initial consolidation pressures and different specimen components on the mechanical and seepage characteristics of consolidated specimens were analyzed. This study provided a theoretical basis for understanding the seepage mechanism of collapse columns.

2. Methods

2.1. Sample Collection. The test samples were taken from the X5 collapse column exposed during the excavation of the 30107 belt transport roadway in Shiquan coal mine of Shanxi Province. Samples mainly consisted of collapse column fillings and broken rock pieces of different sizes, as shown in Figure 1. The X5 collapse column was located in the middle of the belt transport roadway, with a ground elevation of +890–960 m, underground elevation of +425–485 m and buried depth of 425–520 m. According to the analysis of geophysical prospecting and geological data, the overall density of the collapse column was smaller than that of the intact rock. Considering the development characteristics of collapse columns, the load at the exposed location of the collapse column was estimated as ~5 MPa; the collapse column was well developed. According to the field exposure, and sampling, the X5 collapse column was in a relatively dense semicemented state. The collapse column was mainly composed of consolidated filling materials of fuchisia mudstone (FM) and grey (white) mudstone (GWM) as well as

![Figure 1: Sketch of 30107 belt transport roadway passing through X5 collapse column and lithology photos of collapse column exposed at different positions of roadway.](Image 316x618 to 543x705)
broken rock masses of various sizes. The phenomenon of cementation diagenesis was relatively rare. Owing to the structural instability of the collapse column, it was easily loosened and broke during excavation, making field sampling more difficult. Therefore, the Geotechnical Test Method Standard was used for this experiment and the collapse column filling samples were prepared by mixing the collected fuchsia and grey mudstones with skeleton conglomerate having a certain grain size according to the consolidation test method [24, 25].

2.2. Sample Preparation. According to the analysis of actual samples collected at the site, the filling materials in the collapse column were mainly fuchsia mudstone and grey mudstone. First, the mineral composition of mudstone in the collapse column was tested. Powder of two types of mudstone samples were analyzed by performing X-ray diffraction (XRD) using a D-MAX 2500PC X-ray diffractometer, and the experimental results are shown in Figures 2 and 3.

A comprehensive analysis of the components of the mudstones revealed the main components of the fuchsia mudstone being quartz, montmorillonite, albite, chlorite, calcite, kaolinite, and hematite, whereas those of the grey mudstone are quartz, montmorillonite, kaolinite, albite, and chlorite. This shows that the main components of the two mudstones are approximately the same, with fuchsia mudstone comprising calcite and hematite in addition to the components available in the grey mudstone. Because of the presence of hematite, fuchsia mudstone has a purplish-red color.

As shown in Figure 2, the semiquantitative analysis of the XRD pattern revealed that the main components contained in fuchsia mudstone and grey mudstone are thus similar. The main components in fuchsia mudstone are quartz, montmorillonite, albite, chlorite, and calcite, while kaolinite and hematite account for a relatively small proportion. The proportions of montmorillonite, albite, chlorite, and kaolinite are more average. The proportion of kaolinite is higher in grey mudstone, while it is lower in fuchsia mudstone.

The mineral composition of both types of mudstones is complex. They are mainly composed of clay minerals, followed by detrital minerals, epigenetic minerals, and ferromanganese and organic matter. Chlorite and montmorillonite are clay minerals with plasticity, adhesion, and volume expansion capabilities when wet and the ability to block water to a certain extent. In contrast, the consolidation strength of mudstone is weaker than that of conglomerate, with a soft texture and low degree of consolidation, and without obvious recrystallization. The proportion of montmorillonite and chlorite in fuchsia mudstone is higher than that in grey mudstone.

According to the analysis of actual samples obtained from the field, the internal components of collapse columns were rather complicated and contained both fuchsia and grey mudstones. Furthermore, greyish-white medium-fine conglomerates were observed. These three components were mixed, and consolidated specimens were designed with reference to the in situ conditions. The three components were fuchsia mudstone and conglomerate; grey mudstone and sandstone; and fuchsia mudstone, grey mudstone, and sandstone. The procedure of preparing the consolidated specimens is as follows. First, the samples were screened according to the particle size as per test requirements. Next, the fuchsia and grey mudstones were separated, crushed to the appropriate particle size, dried, and sealed. Different filling materials were then mixed with a certain proportion of water and put into a steel mold with a height and diameter of 130 and 50 mm according to the actual exposure of the X5 collapse column (Figure 4). Then, high-pressure consolidation was carried out by using a press under certain preconsolidation given in the early stage. Considering the measurement results of mechanical parameters of field conditions,
samples, the consolidation pressures of 2,500 and 5,000 KPa were determined. According to the consolidation test method, step loading was used to increase the pressure from 25 to 5,000 KPa in 9 levels, as shown in Figure 5. During the consolidation test, the next-stage load was applied when the sample deformation under a single-stage load was not larger than 0.01 mm/h. The initial height of the consolidated specimen after preconsolidation was about 105 mm. The standard specimen size was determined as $\phi 50 \text{ mm} \times 100 \text{ mm}$ after grinding and cutting [26], and the test sample is shown in Figure 6.

2.3. Experimental Equipment. In this study, a triaxial multi-field coupled test system for rocks was used (Figure 7), which is suitable for conducting seepage-stress coupled and conventional mechanical experiments. The test system consisted of a triaxial chamber, a control system, a loading system of axial and confining pressures, a measurement control...
Figure 4: Schematic of the consolidation device.

Figure 5: Grading consolidation pressure.

Figure 6: Consolidated test specimens.

Figure 7: Test system.
system, and a seepage system. The maximum axial, confining, and osmotic pressure in the triaxial chamber were 500, 60, and 60 MPa, respectively. The measurement control system included linear variable differential transformer sensors for the axial strain monitoring as well as circumferential strain sensors. To ensure the accurate measurement of the deformation at the initial stage of loading, the fixture rings for circumferential strain sensors had no gaps with the specimen circumferences.

To understand the permeability changes of consolidated collapse column specimens at different consolidation pressures and with different consolidation components, the experiments were conducted using the steady-state method, which is based on the principle of Darcy’s law, and the

Figure 8: Full stress–strain curve of collapse column fillings under different consolidation pressures.
The expression used for the permeability of a consolidated specimen is as follows [27]:

\[
K_m = \frac{\mu L \Delta Q_m}{A \Delta P \Delta t_m},
\]

where \(K_m\) is the average permeability of sandstone during the time interval of \(\Delta t_m\) (m\(^2\)); \(\mu\) is the fluid viscosity coefficient, and \(\mu = 100.5 \times 10^{-5}\) Pa-s; \(L\) is the height of sandstone specimens (m); \(\Delta Q_m\) is the volume of water flowing through the sandstone specimen during time interval, \(\Delta t_m\) (m\(^3\)); \(A\) is the cross-section of the specimen (m\(^2\)); \(\Delta P\) is the difference in upstream and downstream osmotic pressures during the seepage test; and \(\Delta t_m\) is the interval between different recording point(s).

The temperature of the seepage medium used in the experiment was maintained at 20°C. Based on the measured ground stress test and the calculated karst water pressure, the triaxial compression permeability test was carried out with a confining pressure of 4 MPa and a seepage pressure difference of 2 MPa. Tests were conducted at different consolidation pressures and with three groups of specimen materials with different filling materials. The test procedure was as follows:

1. Place the prepared specimen into the triaxial chamber, install the axial and circumferential strain sensors and the seepage pipelines in turn, adjust the
initial value of the sensors, and ensure that the seepage channel is unimpeded

(2) Close the triaxial chamber, fill it with oil, and let the axial indenter make full contact with the specimen by stress control

(3) Apply the confining pressure of 4 MPa at a rate of 1 MPa/min in a stress-controlled manner, apply the osmotic pressure after the confining pressure has stabilized, and set the osmotic pressure difference to a predetermined value (because the downstream outlet pressure of the seepage flow is kept at atmospheric pressure, the osmotic pressure difference is the upstream inlet water pressure)

(4) After the seepage is stabilized, axial deviator stress is applied at a loading rate of 0.04 mm/min until the specimen yields. During the loading process, the measurement and control system automatically records the stress–strain test curve, records the water pressure stroke and the water flow rate at the downstream outlet of seepage during the test process, and calculates the corresponding real-time permeability during the loading process of sandstone in a period of time

(5) End the test when the plastic strain of specimens exceeds the sensor range

(6) Repeat the above procedure for other specimens under different conditions to obtain the specimen permeability at different consolidation pressures and with different filling components

3. Results and Discussion

3.1. Stress–Strain Characteristics of Consolidated Collapse Column Specimens. The stress–strain curves of consolidated collapse column specimens during the triaxial compressive seepage tests are shown in Figure 8 and have typical creep-like characteristics.

The stress–strain curve was roughly divided into the following three stages: (i) Compression stage (OA), during which the original volume of pores and microfractures inside consolidated specimens were large. Under the axial load, the original pore volume decreased and the consolidation degree of specimens further increased. The stress–strain curve showed an “upward-convex” growth, (ii) elastic deformation stage (AB), where the line elastic characteristics of consolidated specimens of collapse column fillings showed great variability. The consolidated specimens made of fuchsia mudstone, grey mudstone, and conglomerate showed partially elastic characteristics. With the increase of consolidation pressure, the strain range corresponding to the elastic characteristics increased gradually. Meanwhile, the consolidated specimen made of fuchsia mudstone did not show ideal elastic deformation characteristics; (iii) Plastic creep-like stage (BC), during which the increase rate of axial load gradually slowed down with increasing strain, and the consolidated specimens gradually showed plastic creep-like characteristics. The microfractures inside the specimens at this stage first expanded rapidly and connected, and then the expanded microfractures closed again with increasing load. Then, the void volume decreased again.
3.2. Effects of Consolidation Pressure on Stress and Permeability. During the loading process of the consolidated specimens, internal pores, and microfractures were initially compacted under initial consolidation and confining pressures. Figure 9 shows the relationship curves of the deviatoric stress, axial strain, and permeability of specimens with different components under different initial consolidation pressures.

As shown in Figure 9, the permeability of consolidated specimens under different conditions had an obvious four-stage evolution of gradual decrease, stable development, rapid increase, and slow decrease with increasing axial strain. The stages partially corresponded to the three-stage variation characteristics of the deviatoric stress–axial strain curve, but there was also a slight difference. For example, at a consolidation pressure of 5 MPa, the permeability of consolidated specimens made of fuchsia mudstone, grey mudstone, and conglomerate gradually decreased from $1.63 \times 10^{-16}$ m$^2$ to $3.36 \times 10^{-17}$ m$^2$, steadily increased to $4.8 \times 10^{-17}$ m$^2$, then rapidly increased to $2.7 \times 10^{-16}$ m$^2$, and finally slowly decreased to $2.65 \times 10^{-17}$ m$^2$. The consolidated specimens in other working conditions all had similar evolutionary patterns. Figure 6 shows that for consolidated specimens with the same components, higher initial consolidation pressures would reduce the permeability. This was mainly because as the initial consolidation pressure increased, the initial pore space of consolidated specimens decreased. Then, the microfracture opening inside the specimens became smaller, which led to a smaller permeability value. Under the same consolidation pressure, specimens made of grey mudstone and conglomerate had the maximum permeability, specimens made of fuchsia mudstone and conglomerate had the minimum permeability, and specimens made of fuchsia mudstone, grey mudstone, and conglomerate had a median permeability. This was mainly due to the unique hydration of fuchsia mudstone, which can quickly fill the specimens owing to the physical properties of plasticity and water absorption of the clay minerals inside fuchsia mudstone. It can reduce the opening of fractures and narrow the permeability channels, which in turn led to a smaller permeability value for specimens containing fuchsia mudstone. The above pattern indicated that the initial consolidation pressure and the fuchsia mudstone had a significant effect on the permeability change of the consolidated specimens.

3.3. Effects of Different Components on Permeability. The permeability of consolidated specimens during triaxial compression was related to the pore compactness inside the specimens, and the permeability variation was closely related to the specimen composition under the same initial consolidation pressure with approximately the same microfracture opening. Figure 10 shows the variation of the triaxial compression permeability of specimens with different components under the same initial consolidation pressure (taking the initial consolidation pressure of 5 MPa as an example).

To study the impact of different components on the specimen permeability, the relationship curves between the permeability and axial strain of consolidated specimens made of three different components are plotted in the figure. At the early stage of test loading, the initial permeability of consolidated specimens was large when the axial strain was less than $0.2 \times 10^{-3}$, and the mean values of permeability of consolidated specimens made of different components
were $2.39 \times 10^{-16}$ m$^2$, $1.63 \times 10^{-16}$ m$^2$, and $1.18 \times 10^{-16}$ m$^2$, respectively. The initial permeability of consolidated specimens containing grey mudstone and conglomerate was higher than those of specimens made of fuchsia mudstone, grey mudstone, and conglomerate and specimens made of fuchsia mudstone and conglomerate by 46.6% and 102.5%, respectively. This was mainly caused by the water-adhesive and swelling properties of fuchsia mudstone. With the increase of the axial load, the axial strain increased. When the axial strain reached $2.0 \times 10^{-2}$, the permeability of consolidated specimens successively entered the plastic yielding stage. The microfractures between conglomerates gradually expanded and connected; thus, the volume of specimens expanded, and the permeability of specimens gradually increased to the highest value. In the plastic yielding stage, the average permeability of the specimens containing fuchsia mudstone, grey mudstone, and conglomerate was $4.56 \times 10^{-17}$ m$^2$, that of specimens containing grey mudstone and conglomerate was $6.54 \times 10^{-17}$ m$^2$ and that of specimens containing fuchsia mudstone and conglomerate was $3.98 \times 10^{-17}$ m$^2$. Because of its creep like characteristics, the middle part of the consolidated sample bulged with the increase in the axial load and stable seepage occurred in the consolidated specimen. However, the consolidated specimen was not significantly damaged, and no obvious macroscopic fractures were produced on the surface of the specimen. Thus, the permeability of the consolidated specimen in the yielding creep-like stage was mainly influenced by the viscosity and swelling of the mudstone in the specimen.

### 3.4. Porosity Variation Characteristics: Porosity Analysis

The porosity variation characteristics can well reflect the mechanical behaviors of samples [28–30]. To study the porosity change characteristics, the Image-Pro Plus analysis software was used to binarize the sample images before and after consolidation tests with threshold segmentation technology (Figure 11). After performing analyses and calculations, the dichotomy threshold processing map and pore distribution map were obtained [31–33]. The porosity results are shown in Table 1, and the pore distribution map is shown in Figure 12.

According to Figure 12 and Table 1, the following three conclusions can be made. First, the sample porosity changes were consistent with the consolidation pressure changes. As the consolidation pressure increased from 2.5 MPa to 5 MPa, the porosity of the consolidated fuchsia mudstone specimens decreased from 0.02035 to 0.00803 and that of the consolidated specimens of mixed grey mudstone and conglomerate decreased from 0.01274 to 0.00863 and that of the consolidated specimens of mixed fuchsia mudstone, grey mudstone, and conglomerate decreased from 0.01723 to 0.00872. Second, after the triaxial compression seepage test, the porosity of consolidated specimens decreased markedly compared with the initial porosity. Under the consolidation pressure of 2.5 MPa, the porosity of the consolidated fuchsia mudstone specimens decreased from 0.02035 to 0.01666 and that of the consolidated specimens of mixed grey mudstone and conglomerate decreased from 0.01274 to 0.01182 and that of the consolidated specimens of mixed fuchsia mudstone, grey mudstone, and conglomerate decreased from 0.01723 to 0.01489. Secondly, after the triaxial compression seepage test, the porosity of consolidated specimens decreased markedly compared with the initial porosity. Under the consolidation pressure of 2.5 MPa, the porosity of consolidated specimens with three different components decreased from 0.02035, 0.01274, and 0.01723 to 0.00872, 0.00846, and 0.00686. The decrease ratios were 57.14%, 33.63%, and 60.19%, respectively. Under a consolidation pressure of 5 MPa, the porosity of consolidated specimens of three different components was reduced from

### Table 1: Porosity analysis before and after the test.

| Different components of consolidated specimens | Initial consolidation pressure | Initial porosity | Posttest porosity |
|-----------------------------------------------|--------------------------------|-----------------|------------------|
| Fuchsia mudstone, conglomerate                 | 2.5 MPa                        | 0.01895         | 0.00803          |
|                                               |                                | 0.02174         | 0.00941          |
| Average                                       |                                | 0.02035         | 0.00872          |
| Fuchsia mudstone, conglomerate                 | 5 MPa                          | 0.01542         | 0.00883          |
|                                               |                                | 0.01789         | 0.00938          |
| Average                                       |                                | 0.01666         | 0.00911          |
| Grey mudstone, conglomerate                    | 2.5 MPa                        | 0.01218         | 0.00863          |
|                                               |                                | 0.01330         | 0.00828          |
| Average                                       |                                | 0.01274         | 0.00846          |
| Grey mudstone, conglomerate                    | 5 MPa                          | 0.01065         | 0.00602          |
|                                               |                                | 0.01299         | 0.00797          |
| Average                                       |                                | 0.01182         | 0.00700          |
| Fuchsia mudstone, grey mudstone, conglomerate  | 2.5 MPa                        | 0.01720         | 0.00682          |
|                                               |                                | 0.01726         | 0.00690          |
| Average                                       |                                | 0.01723         | 0.00686          |
| Fuchsia mudstone, grey mudstone, conglomerate  | 5 MPa                          | 0.01502         | 0.00745          |
|                                               |                                | 0.01476         | 0.00676          |
| Average                                       |                                | 0.01489         | 0.00711          |
0.1666, 0.01182, and 0.01489 to 0.00911, 0.00700, and 0.00711, decreasing by 45.33%, 40.82%, and 52.28%, respectively. Thirdly, the change in porosity of the collapse column fillings was the main cause of the change in permeability. The variation of permeability in the triaxial compression seepage test maintained the same trend as the porosity of the consolidated specimens made of filling materials. In the initial compression stage, the permeability of consolidated specimens gradually decreased with the increase of the deviator pressure, mainly because the pores and microfractures inside the specimen were gradually closed under the confining and deviator pressures, and the permeability decreased accordingly. In the next stage, there developed vertical microcracks between conglomerates inside the consolidated sample, which also went through further expansion and development. At a certain point, microseepage cracks were developed. As the pore structure increased, the permeability increased to a maximum value. In the plastic stage of mudstone, the pores and microfractures were filled owing to the viscosity and plasticity of wetted mudstone inside the sample. Thus, the pore structure was further reduced, and the porosity was reduced. Consequently, the sample permeability gradually decreased. This process coincided with the permeability changes. Therefore, changes in the porosity of filling materials affect changes in permeability of the consolidated specimens.

4. Conclusions

(1) The full stress–strain curve of the consolidated collapse column specimens can be classified as the compression stage, linear deformation stage, and creep-like stage. The overall permeability during the test showed an obvious four-stage evolution of gradual decrease, stable development, rapid increase, and gradual slow decrease, which largely corresponded to the change characteristics of the three stages in the full stress–strain curve.

(2) The deformation characteristics of recombined structures specimens of collapse column fillings showed an obvious initial consolidation pressure effect. The elastic modulus and creep-like strength increase with the increase of the consolidation pressure. The full stress–strain curve demonstrated a three-stage evolution of compression, elastic deformation, and plastic creep.

(3) At the initial stage of loading, the permeability of consolidated specimens was mainly influenced by the initial consolidation pressure. Under a higher initial consolidation pressure, the permeability became smaller. When the consolidated specimens were gradually compacted after the initial loading, the main factor affecting the permeability change is the component of consolidated specimens. With a higher content of fuchsia mudstone, the permeability became smaller.

(4) The consolidation pressure of the recombined structures collapse column specimens had a significant impact on their permeability characteristics. The specimen porosity was analyzed using the Image-Pro Plus software, and it was found that the specimen porosity showed a decreasing trend with an increasing consolidation pressure. The porosity of recombined structures specimens after the test was further reduced under the action of axial pressure. The change in porosity inside the consolidated specimens led to a subsequent change of permeability.
Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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