

Article

Experimental Study on the Creep Behavior and Permeability Evolution of Tuff Under Unloading Confining Pressure with Seepage–Stress Coupling Effects

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Abstract

The long-term stability of deep underground excavations near aquifer-bearing strata is primarily controlled by the time-dependent deformation and permeability changes in the surrounding rock mass under the combined effects of mechanical loading and groundwater seepage. This study experimentally investigates the creep behavior and permeability evolution of tuff specimens subjected to stepwise reductions in confining pressure under coupled seepage and stress conditions. Conventional triaxial compression tests were conducted to determine the peak strength at confining pressures of 10, 15, and 20 MPa. Subsequently, triaxial creep tests were performed, maintaining axial stress at 70% of the previously established peak strength, with a constant seepage pressure of 4 MPa, while progressively decreasing the confining pressure. The results clearly reveal a three-stage creep process—with instantaneous, steady-state, and accelerated phases—with the radial strain exceeding axial strain and ultimately dominating at failure. This indicates that failure is characterized by significant volumetric expansion. At the specified initial confining pressures of 10 MPa, 15 MPa, and 20 MPa, the tuff specimens exhibited volumetric strains of -1.332 , -1.119 , and -0.836 at failure, respectively. Permeability evolution depends on the creep stage, showing a pronounced increase during the accelerated creep phase that often surpasses the cumulative permeability changes observed earlier. The specimen's permeability at failure increased by factors of 3.97, 3.21, and 3.61 compared to the initial stage of the experiment, respectively. Additionally, permeability evolution exhibits a strong functional relationship with volumetric strain, which can be effectively modeled using an exponential function. The experimental findings further indicate that, as the confining pressure is gradually reduced, the permeability evolves following a clear exponential trend. Additionally, a higher initial confining pressure slows the rate at which permeability increases. These findings clarify the three-stage creep behavior and the associated evolution of the permeability index in tuff under coupled seepage–stress conditions. Additionally, they present a quantitative model linking permeability to volumetric strain, offering both a theoretical foundation and a new approach for assessing the long-term stability risks of deep underground engineering projects.

Keywords: unloading confining pressure; seepage–stress coupling; experimental study; permeability; creep; triaxial compression test



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1. Introduction

During the excavation of deep roadways, the stress field within the surrounding rock undergoes dynamic changes due to excavation-induced unloading, resulting in localized stress concentrations. When these stresses exceed the strength threshold of the surrounding rock, they initiate localized damage that subsequently develops into macroscopic deformation and loosening in adjacent areas [1–3]. Over time, the in situ stress continues to drive progressive deformation of the surrounding rock, manifested as the time-dependent accumulation of damage within the rock mass. Deep underground excavations are inherently vulnerable to groundwater-related hazards, where the combined effects of excavation-induced disturbances and seepage forces generate coupled hydro-mechanical stress states within the host rock [4–6]. Consequently, post-excavation damage evolution in rock masses represents a time-dependent hydro-mechanical coupling process, highlighting the need for experimental investigation of mechanical properties and permeability of surrounding rocks in roadways located near aquifers.

During the excavation of underground engineering, the rock mass undergoes unloading disturbances, resulting in temporal changes in its properties. Therefore, studies on the evolution of rock mechanical behavior and permeability under the seepage–stress coupling effects must consider the effects of unloading and creep [7–9].

Numerous studies have been performed on mechanical behavior of rocks under unloading and creep conditions [10–13]. Heap et al. [14] conducted triaxial creep experiments on saturated Darley Dale sandstone specimens, elucidating the relationship between axial strain rate and differential stress, while also examining the effect of confining pressure on the creep strain rate. Their results revealed that time-dependent brittle creep in sandstone was highly sensitive to differential stress, strongly inhibited by effective confining pressure, and minimally influenced by pore fluid pressure, as supported by microstructural and acoustic emission analysis. These findings provide critical constraints for understanding and modeling the long-term, time-dependent deformation of brittle rock in the Earth's crust, with fundamental implications for assessing tectonic processes and subsurface engineering stability. Liu et al. [15] produced fractured marble samples using a triaxial unloading method and subsequently subjected these specimens to triaxial creep tests under various stress states. Their findings indicated that lateral creep measurements of fractured marble more effectively capture creep characteristics, making them more suitable for assessing the long-term strength of fractured marble. Xiao and Mo [16] investigated the creep energy dissipation and damage evolution characteristics of white sandstone under confining pressure unloading after long-term stress, using a novel method to determine the long-term strength stress level under different confining pressures. The findings provided critical insights into the damage mechanisms of rocks during deep excavation-induced unloading, offering valuable guidance for stability prediction and risk assessment in underground engineering projects.

Extensive research has shown that hydromechanical coupling leads to highly complex evolutionary changes in the mechanical and permeability properties of rocks [17–20]. Huang et al. [21] investigated the evolution of permeability properties of limestone under various triaxial stress paths, including conventional loading, axial pressure increase with confining pressure unloading, and creep unloading conditions. The results demonstrate that permeability evolution is stress-path dependent, exhibiting distinct patterns such as a Gaussian function relationship between permeability loss rate and effective stress during compression, and an exponential increase in permeability change rate with cumulative unloading during confining pressure reduction. Yan et al. [22] investigated the coupled mechanical-permeability response of basalt through triaxial unloading-induced creep tests, providing foundational insights for long-term stability assessments under

hydro-mechanical coupling conditions. The results revealed a tensile–shear composite failure mode and demonstrate that both the steady-state creep rate and permeability exhibit an exponential relationship with confining pressure, with permeability showing distinct stage-wise evolution during unloading. These findings provided critical insights for predicting the long-term stability and seepage evolution of basaltic rock masses under complex stress paths, with direct implications for the safety assessment of large hydropower project foundations. Oda, Takemura and Aoki [23] conducted triaxial tests on fracture-damaged granite specimens, quantitatively tracking permeability changes throughout loading to characterize the coupled dynamics between damage evolution and permeability variation. Based on triaxial compression tests on Inada granite, a microstructurally based permeability tensor model was developed, revealing a 2–3 orders of magnitude permeability increase upon failure and essentially isotropic flow behavior despite anisotropic crack growth. This framework provided a critical link between mechanical damage and hydraulic properties, enabling more accurate prediction of the hydro-mechanical response of fractured crystalline rocks in geotechnical and geophysical systems. Zhu et al. [24] examined creep deformation and permeability evolution in paleo-weathered rocks subjected to triaxial cyclic loading–unloading confining pressure tests, revealing distinct creep stages accompanied by phase-dependent permeability evolution patterns. Their study provided crucial mechanistic insights into the leakage and regional water-level decline in cretaceous aquifers by elucidating the creep deformation and non-monotonic permeability evolution of a key paleo-weathered aquiclude under realistic triaxial unloading–loading stress paths. Zhang et al. [25] investigated the seepage failure mechanisms and disaster modes in water-rich ultracataclasite strata for diversion tunnels, identifying three distinct disaster modes (water inrush, mud inrush, and face collapse) and five evolutionary stages, while establishing critical hydraulic gradients of 3.1 and 5.0 for mode transitions and significant correlations between the thickness of the water-blocking rock mass and key disaster parameters. Zhang et al. [26] investigated the deformation and seepage characteristics of fractured rock masses under loading–unloading conditions and varying gas pressures through fluid–solid coupling triaxial tests. Their findings provided a critical mechanical basis for predicting and preventing hazardous gas leaks during deep underground excavations by quantifying the coupled hydro-mechanical response of rocks to unloading. Some previous research results related to this study are summarized in Table 1.

However, excavating roadways in water-rich geological formations is influenced by a combination of rock unloading, creep deformation, and seepage processes [27–30]. The evolution of permeability characteristics and their hydro-mechanical correlations during unloading confining pressure creep have been insufficiently investigated.

Based on the research gaps, in this study, conventional triaxial compression tests were initially performed on tuff specimens, which were subjected to confining pressures of 10 MPa, 15 MPa, and 20 MPa. Additionally, creep tests involving hydro-mechanical coupling were conducted under unloading of the confining pressure, maintaining the specified pressure levels. The study revealed the creep behavior and permeability evolution characteristics of tuff specimens under the coupled seepage–stress effects during the unloading of confining pressure. This research elucidated the interrelationship among permeability evolution, strain, and confining pressure under different initial confining pressure conditions.

Table 1. Some previous research findings related to this study.

Author	Materials	Methods	Investigation Purpose
Heap et al. [14]	Darley Dale sandstone	triaxial creep test	relationship between axial strain rate and differential stress
Liu et al. [15]	fractured marble	triaxial creep test	long-term strength of fractured marble
Xiao and Mo [16]	white sandstone	triaxial creep test	long-term strength stress level under different confining pressures
Huang et al. [21]	limestone	various triaxial stress paths	evolution of permeability properties
Yan et al. [22]	basalt	triaxial unloading-induced creep tests	coupled mechanical–permeability response of basalt
Oda, Takemura and Aoki [23]	fracture-damaged granite	triaxial tests	coupled dynamics between damage evolution and permeability variation
Zhu et al. [24]	paleo-weathered rocks	triaxial cyclic loading–unloading confining pressure tests	creep deformation and permeability evolution
Zhang et al. [25]	water-blocking rock	seepage failure tests	seepage failure mechanisms and disaster modes
Zhang et al. [26]	fractured rock	fluid–solid coupling triaxial tests	deformation and seepage characteristics

2. Materials and Methods

2.1. Experimental Materials and Specimen Preparation

The main lithology in the study area is tuff, which features a relatively dense rock mass and poorly developed fracture networks, located next to the aquifer. The geological cross-section is shown in Figure 1. The tuff specimens employed in this study were obtained from the auxiliary slope associated with the capacity expansion project at Luohe Iron Mine. The representative rock core samples collected from the engineering site are shown in Figure 2. According to the recommendations of the International Society for Rock Mechanics (ISRM) and the testing requirements of this study, the tuff specimens were fabricated into a cylindrical shape with a height of 100 mm and a diameter of 50 mm [31].

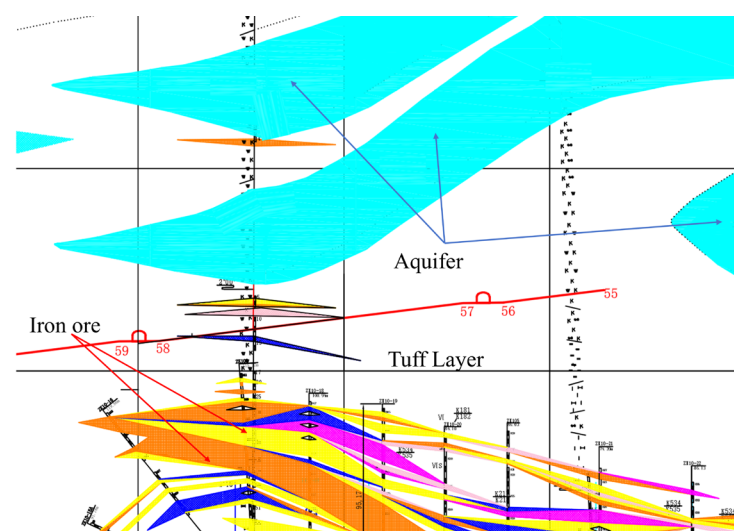


Figure 1. Geological cross-section of the study area (the red arrow points to the iron ore, and the blue arrow points to the aquifer).

Before conducting the triaxial unloading confining pressure creep test under seepage stress, the tuff specimens required pre-saturation, which was achieved through vacuum pumping as a method of forced saturation. During the saturation process, the water level inside the vessel was maintained above the height of the tuff specimens. Forced saturation

was considered complete when no air bubbles were observed escaping during the pumping process, and pumping continued for at least 24 h to ensure consistent saturation across rock specimens and to guarantee the effectiveness of the vacuum saturation process [32]. The basic physical and mechanical properties of tuff were determined in the preliminary stage, as shown in Table 2.



Figure 2. Typical core samples obtained from the study area.

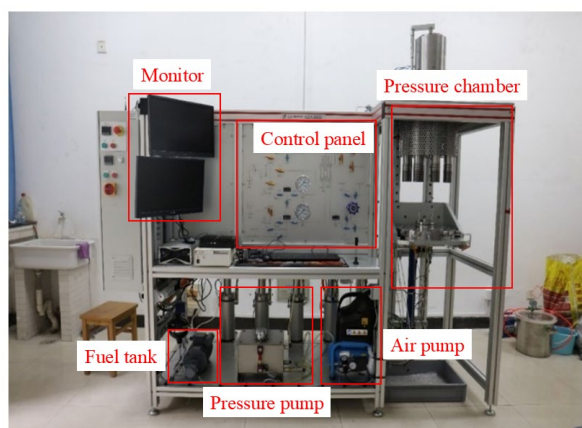
Table 2. Basic physical and mechanical properties of rocks in this study.

No.	Density ($\text{kg}\cdot\text{m}^{-3}$)	UCS (MPa)	BTS (MPa)	Elasticity Modulus (GPa)	Poisson's Ratio
1-1	3035.75	91.65	6.39	21.53	0.21
1-2	3102.26	96.78	7.13	22.62	0.19
1-3	3088.56	92.55	6.94	20.89	0.19
Average value	3075.52	93.66	6.82	21.68	0.20

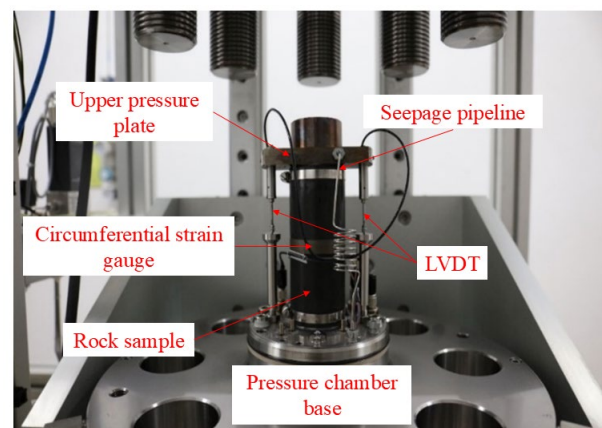
UCS refers to the uniaxial compressive strength, BTS refers to the Brazilian splitting tensile strength.

2.2. Experimental Equipment and Process

The experiment was conducted using the Rock Top multi-field coupling experimental system, developed by the School of Resources and Geosciences at China University of Mining and Technology. This system enables single- or multi-field coupling tests involving stress, temperature, and seepage. The apparatus is designed to apply a maximum axial load of 1500 kN and a maximum confining pressure of 100 MPa, meeting the pressure and seepage conditions required for this study. A schematic diagram of the experimental setup is shown in Figure 3 [33].



(a) Equipment appearance.



(b) Pressure chamber.

Figure 3. Rock Top multi-field coupling experimental system: (a) appearance of the experimental equipment; (b) pressure chamber of the experimental equipment [33].

Based on the in situ stress state of the rock mass, confining pressures of 10 MPa, 15 MPa, and 20 MPa were selected for the conventional triaxial compression tests. For each confining pressure level, at least three specimens were tested. At the start of the experimental procedure, both the confining pressure and axial stress were applied to their target values. Subsequently, axial loading was performed under constant displacement rate of 0.05 mm/min until the specimen failed.

Creep tests involving unloading under coupled seepage and stress conditions were conducted at the previously specified confining pressures. Three specimens were tested under each initial confining pressure condition. The axial stress was maintained at 70% of the peak axial stress determined from conventional triaxial compression tests corresponding to each confining pressure [34]. The experimental procedure of this study is shown in Figure 4. The seepage pressure was set at 4 MPa, consistent with relevant engineering geological conditions. Seepage pressure was applied via the seepage module, which utilizes two high-precision flow pumps to simultaneously deliver seepage pressure to the upper and lower ends of the specimen. Via the seepage module, the seepage pressure can be maintained at a consistent level. Throughout the tests, axial stress was held constant, while confining pressure was reduced in increments of 2 MPa per stage at a rate of 0.05 MPa/s. Each creep stage was sustained for 48 h before proceeding to the subsequent unloading stage, continuing until specimen failure occurred. The test parameters are summarized in Table 3, and the detailed experimental procedure is outlined as follows:

- (1) The saturated rock specimen was placed inside the triaxial pressure chamber, ensuring the correct positioning and calibration of both the sensor and the seepage apparatus.
- (2) Confining pressure was applied at a controlled rate of 1 MPa per minute until the target value was reached.
- (3) After establishing the confining pressure, the seepage pressure was increased to 4 MPa at a rate of 1 MPa per minute.
- (4) Once the seepage pressure stabilized, axial stress was applied at a rate of 0.05 MPa per second until the preset axial stress value was reached. The axial stress was then maintained constant until the end of the test.
- (5) Upon completion of axial stress loading, the confining pressure was gradually reduced at a rate of 0.05 MPa per second. The unloading process was in increments of 2 MPa, with a 48 h holding period at each decrement, continuing until the specimen experienced ultimate failure.

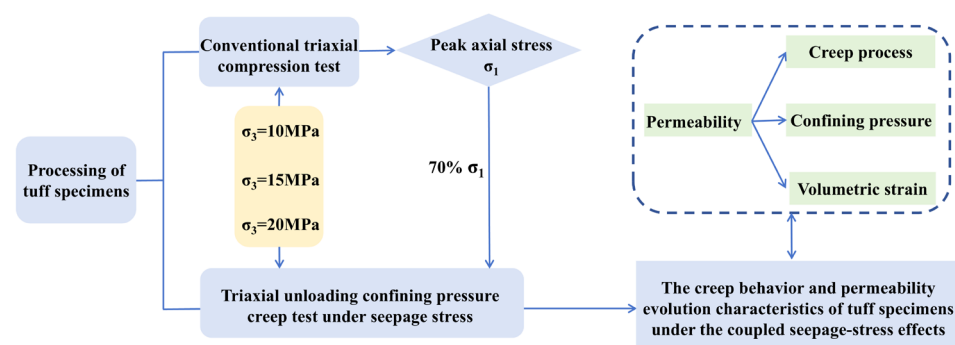


Figure 4. The research and experimental procedure of this study.

Table 3. Test parameters of the unloading confining pressure triaxial creep test.

Initial Confining Pressure (MPa)	Seepage Pressure (MPa)	Axial Stress (MPa)	Confining Pressure Stage (MPa)	Creep Duration per Stage (h)
10	4	70% σ_1 ¹	10, 8, 6, 4	48
15	4	70% σ_1	15, 13, 11, 9, 7	48
20	4	70% σ_1	20, 18, 16, 14, 12, 10	48

¹ σ_1 refers to the peak axial stress in conventional triaxial compression tests.

3. Experiment Results and Discussion

3.1. Results of Conventional Triaxial Compression Tests

During triaxial compression testing, rocks experienced a progressive failure mechanism characterized by processes such as compaction, fracturing, crack propagation, and permeation within the rock mass. Based on the distinct states exhibited by the rock throughout the testing procedure, this failure process is divided into five discrete stages: the compaction stage, the elastic stage, the stable crack propagation stage, the unstable crack propagation stage, and the post-peak deformation and failure stage. The evolution of stress–strain behavior exhibited by specimens subjected to three different confining pressure conditions is shown in Figure 5.

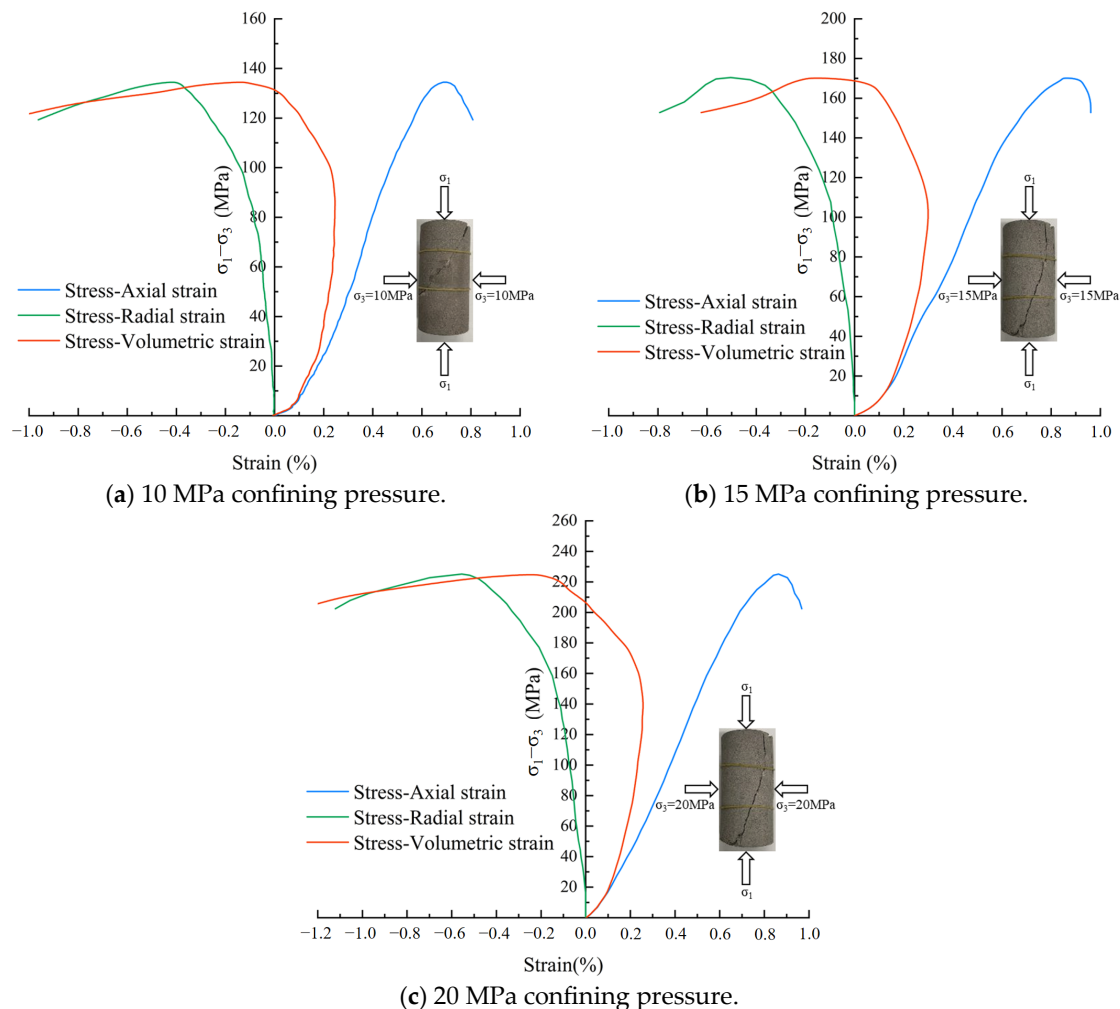


Figure 5. The stress–strain curves of specimens under conventional triaxial compression test: (a) evolution of stress–strain behavior under 10 MPa confining pressure condition; (b) evolution of stress–strain behavior under 15 MPa confining pressure condition; (c) evolution of stress–strain behavior under 20 MPa confining pressure condition.

Conventional triaxial compression tests conducted under three different confining pressure conditions demonstrated that higher confining pressure results in greater peak deviatoric stress, as shown in Table 4. The strain response during the testing process clearly progresses through several stages: compaction, linear deformation, nonlinear deformation, and failure.

Table 4. The results of conventional triaxial compression test.

Confining Pressure σ_3 (MPa)	σ_1 (MPa)	$\sigma_1 - \sigma_3$ (MPa)	Axial Peak Strain (%)	Radial Peak Strain (%)	Elastic Modulus (GPa)	Poisson's Ratio
10	144.45	134.45	0.702	−0.426	28.57	0.24
15	185.43	170.43	0.847	−0.504	29.38	0.22
20	245.11	225.11	0.863	−0.555	33.17	0.21

Based on the fitted curve derived from the experimental data, it is inferred that the parameters of the Mohr–Coulomb strength criterion are $F = 10.066$ and $Q = 40.6733$. Consequently, the shear strength parameters of the rock are determined to be a cohesion (c) of 6.41 MPa and an internal friction angle (φ) of 55.01° .

3.2. Experimental Analysis of Creep Under Unloading Confining Pressure Coupled with Seepage Stress

Figure 6 shows the temporal progression of axial strain, radial strain, and volumetric strain under varying confining pressures during triaxial creep tests with seepage–stress coupling. The corresponding strain measurements at each confining pressure level are stated in Table 5. The strain curves exhibit the characteristic phases of instantaneous creep, steady-state creep, and accelerated creep, which was previously confirmed by numerous scholars [35–37]. The final stage of accelerated creep corresponds to specimen failure. In these experiments, confining pressure was decreased in increments of 2 MPa. It was observed that specimens subjected to higher initial confining pressures failed at correspondingly higher confining pressures, which in turn extended the total duration of creep [12]. Specifically, the durations until failure for initial confining pressures of 10 MPa, 15 MPa, and 20 MPa were recorded as 168 h, 208 h, and 260 h, respectively.

Table 5. Results of rock unloading confining pressure creep test under different initial confining pressures.

Initial Confining Pressure (MPa)	Confining Pressure (MPa)	Time (h)	Instantaneous Strain (%)			Total Strain (%)		
			Axial	Radial	Volumetric	Axial	Radial	Volumetric
10	10	48	0.398	−0.134	0.130	0.413	−0.155	0.103
	8	48	0.068	−0.047	−0.026	0.112	−0.110	−0.108
	6	48	0.071	−0.064	−0.057	0.112	−0.118	−0.124
	4	24	0.080	−0.085	−0.090	0.346	−0.839	−1.332
15	15	48	0.411	−0.112	0.187	0.437	−0.130	0.177
	13	48	0.068	−0.041	−0.014	0.085	−0.060	−0.035
	11	48	0.074	−0.075	−0.077	0.096	−0.103	−0.110
	9	48	0.09	−0.131	−0.172	0.135	−0.215	−0.295
	7	16	0.092	−0.145	−0.198	0.265	−0.692	−1.119
20	20	48	0.413	−0.098	0.217	0.442	−0.115	0.212
	18	48	0.071	−0.048	−0.025	0.092	−0.072	−0.052
	16	48	0.072	−0.069	−0.066	0.101	−0.102	−0.103
	14	48	0.082	−0.086	−0.09	0.118	−0.135	−0.152
	12	48	0.088	−0.119	−0.15	0.133	−0.192	−0.251
	10	20	0.095	−0.121	−0.149	0.210	−0.523	−0.836

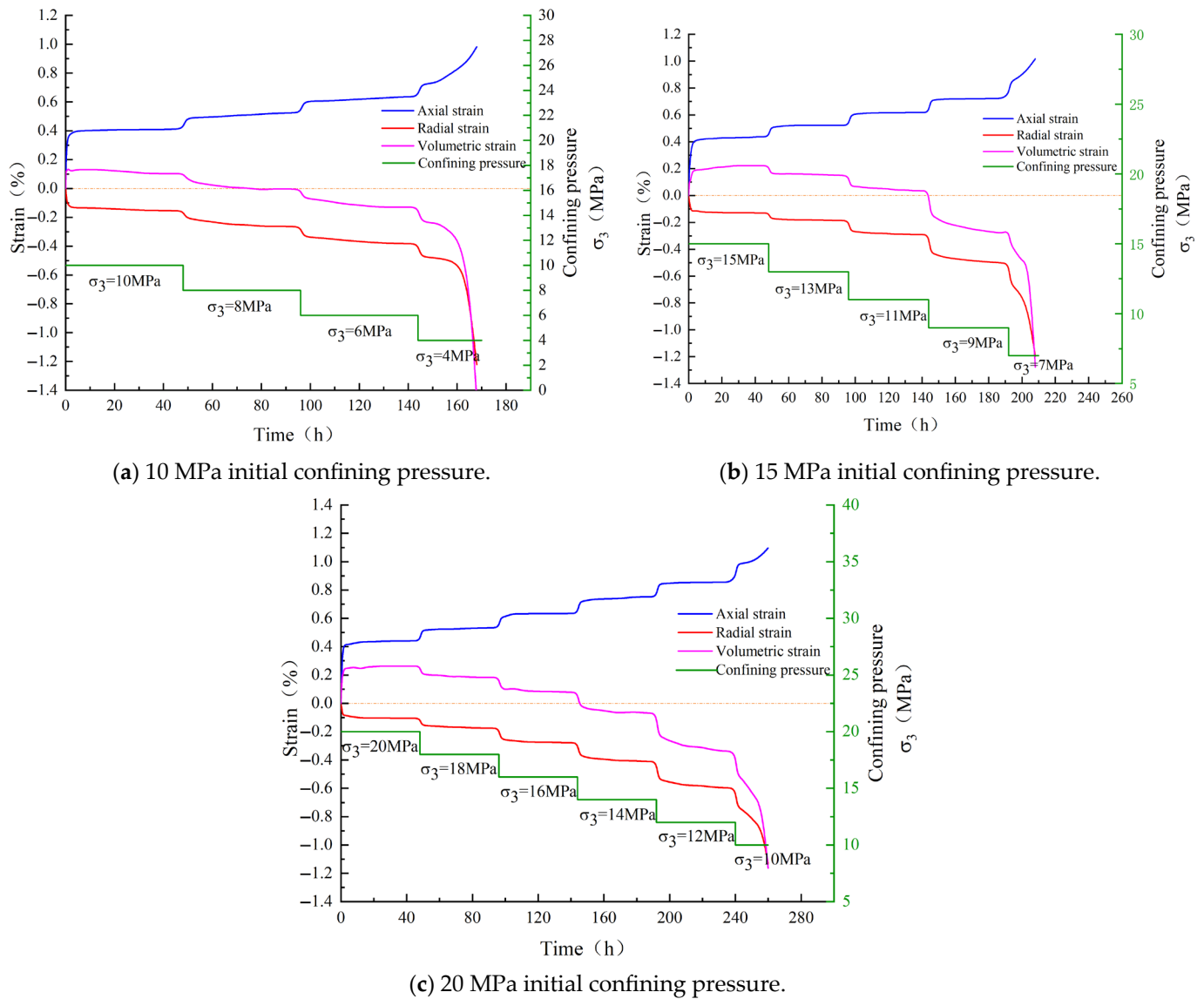


Figure 6. The strain evolution of tuff specimens under unloading confining pressure creep test (the dashed line denotes the boundary where the strain value is zero): (a) strain evolution under 10 MPa initial confining pressure; (b) strain evolution under 15 MPa initial confining pressure; (c) strain evolution under 20 MPa initial confining pressure.

The relationship between initial and final values of axial and radial strains in triaxial creep tests under seepage–stress coupling at different initial confining pressures is shown in Figure 7. As the confining pressure is progressively unloaded step by step during the test, the deviatoric stress gradually increased, leading to an observed increment in both axial and radial strains. The axial strain of the specimen demonstrates a gradual compression, while the radial strain exhibits a corresponding expansion. This shows that while maintaining constant axial pressure and unloading the confining pressure in stages, the specimen undergoes continuous axial compression and radial expansion. Throughout this process, the volumetric strain transitions from gradual compression to eventual expansion with the passage of time, ultimately experiencing a significant increase at the point of specimen failure.

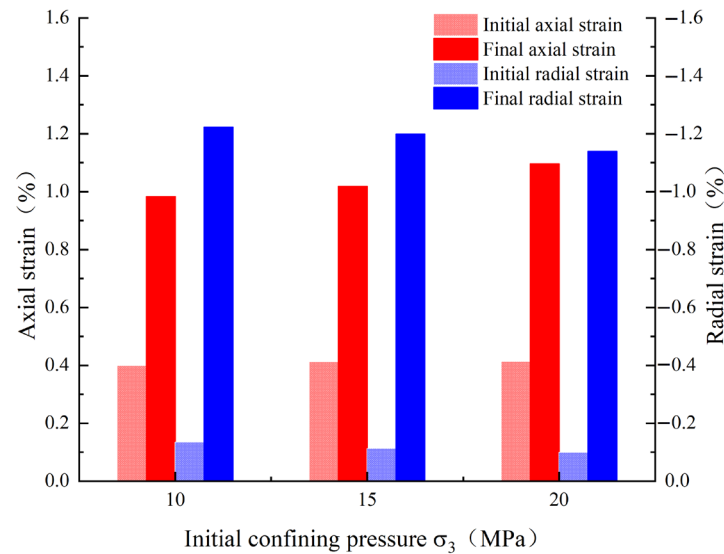


Figure 7. Comparison of axial and radial strain of rock specimens at initial and failure stages under different initial confining pressure conditions in triaxial unloading confining pressure creep tests.

Figure 7 illustrates the correlation between the initial and failure values of axial and radial strains observed in triaxial creep tests. These tests were conducted under seepage–stress coupling conditions at different initial confining pressures. During the testing procedure, the confining pressure is incrementally reduced in a stepwise manner, resulting in a progressive increase in deviatoric stress. This increase corresponds to a rise in both axial and radial strains. Specifically, the specimen’s axial strain shows gradual compressive behavior, whereas the radial strain exhibits a concomitant expansion. These findings suggest that, under conditions of constant axial load and staged unloading of confining pressure, the specimen experiences continuous axial compression alongside radial expansion. The volumetric strain evolves from an initial phase of gradual compression to eventual expansion over time, culminating in a pronounced increase at the point of specimen failure [38].

(1) Under the initial confining pressure of 10 MPa, the specimen demonstrated an initial axial strain of 0.398% and a radial strain of −0.134%. At the point of failure, the axial strain increased to 0.983%, while the radial strain reached −1.222%. These represent increases by factors of 2.47 and 9.12 relative to their initial values, respectively. It is noteworthy that the radial strain at failure was substantially greater than the axial strain, surpassing it by a factor of 1.24.

(2) When subjected to the initial confining pressure of 15 MPa, the specimen exhibited an initial axial strain of 0.411% and a radial strain of −0.112%. Upon failure, the axial strain rose to 1.018%, and the radial strain to −1.199%, corresponding to increases of 2.48 and 10.17 times their initial measurements, respectively. Importantly, the radial strain at failure exceeded the axial strain by a factor of 1.18, indicating a pronounced radial deformation.

(3) At the initial confining pressure of 20 MPa, the specimen showed an initial axial strain of 0.413% and a radial strain of −0.098%. Upon failure, these values increased to 1.096% for axial strain and −1.129% for radial strain, representing increments of 2.65 and 11.52 times their respective initial values. The radial strain at failure marginally exceeded the axial strain by a factor of 1.03.

The experimental findings indicate that the initial axial strain values in rock specimens typically exceed the corresponding radial strain values. However, as the creep unloading process progresses incrementally, the radial strain increases at a faster rate than the axial strain, eventually surpassing it at the point of final failure [39]. Additionally, a

pronounced increase in radial strain magnitude is observed at specimen failure, indicating a rapid progression of volumetric strain and highlighting distinct characteristics of volumetric expansion.

The analysis of triaxial creep tests on rocks subjected to seepage–stress coupling reveals that radial strain is more sensitive to the unloading of confining pressure than axial strain. This increased sensitivity is primarily due to the progressive reduction in radial confinement imposed on the specimen during the confining pressure unloading phase, which is further influenced by the presence of pore water pressure within fracture networks. Consequently, the progression of radial strain continuously accelerates throughout the unloading process.

As shown in Figure 8, the angle between the principal fracture and the specimen's cross-sectional plane at failure ranged from 70° to 90° under three different initial confining pressure conditions. At the initial confining pressure of 10 MPa, the specimen developed two primary fractures, accompanied by numerous minor cracks, with the average length of the main fractures measuring approximately 120 mm. When subjected to the initial confining pressure of 15 MPa, the specimen exhibited a single principal fracture along with several smaller cracks nearby, and the main fracture length was about 105 mm. At the initial confining pressure of 20 MPa, the specimen showed only one main fracture with minimal secondary cracking, and the fracture length was approximately 80 mm. Higher initial confining pressure suppresses the formation of cracks. The failure characteristics observed in the tuff specimens further supported the developmental patterns of volumetric strain [10].

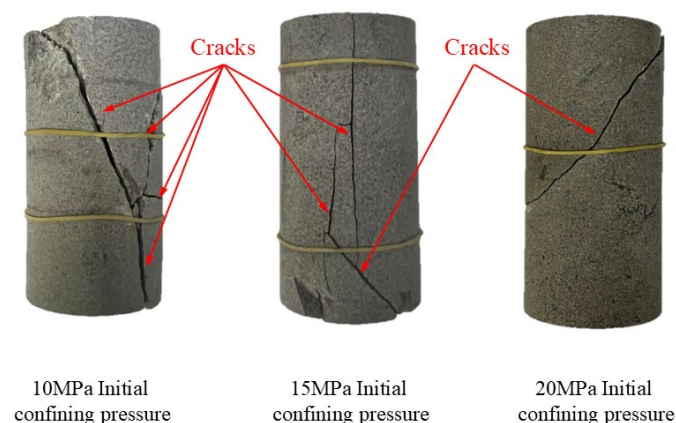
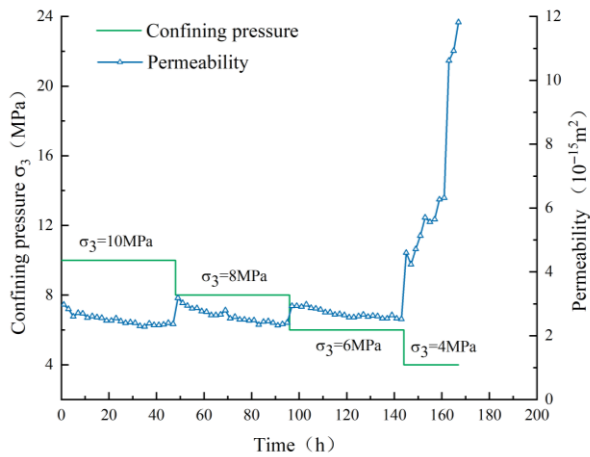


Figure 8. Failure modes of certain tuff experimental specimens.

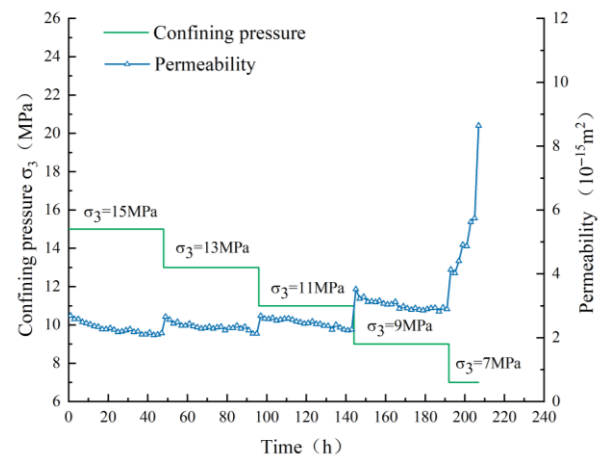
3.3. Analysis of the Evolution Pattern of Permeability During the Tests

The patterns of permeability evolution observed during rock unloading creep tests under varying initial confining pressures exhibit a notable degree of similarity. The time progression of permeability at different confining pressure levels is illustrated in Figure 9.

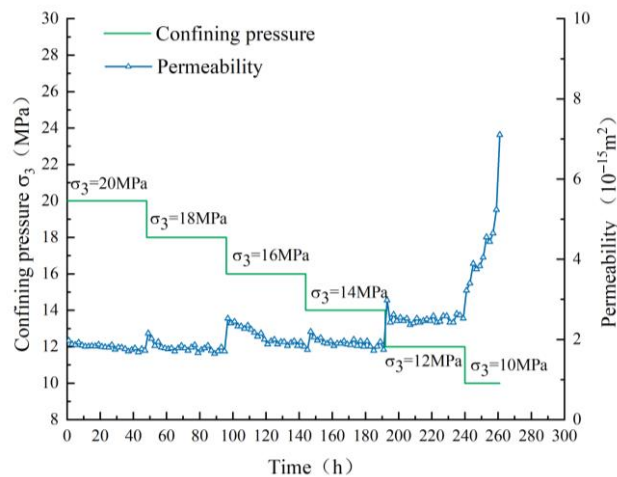
During the initial phases of the experiments, under applied loads of 10 MPa, 15 MPa, and 20 MPa, permeability gradually decreases. Subsequently, throughout the unloading and creep processes, permeability exhibits notable transient fluctuations and characteristic creep behavior. Before specimen failure, each phase of confining pressure unloading causes a slight increase in permeability. Thereafter, during the steady-state creep stage, permeability progressively decreases and approaches a stable value. Additionally, within each creep stage, permeability consistently remains higher than in the preceding stage.



(a) 10 MPa initial confining pressure.



(b) 15 MPa initial confining pressure.



(c) 20 MPa initial confining pressure.

Figure 9. Permeability evolution of rock unloading confining pressure creep test: (a) permeability evolution under 10 MPa initial confining pressure; (b) permeability evolution under 15 MPa initial confining pressure; (c) permeability evolution under 20 MPa initial confining pressure.

At initial confining pressures of 10 MPa, 15 MPa, and 20 MPa, the corresponding initial permeabilities were measured as $2.974 \times 10^{-15} \text{ m}^2$, $2.691 \times 10^{-15} \text{ m}^2$, and $1.969 \times 10^{-15} \text{ m}^2$, respectively. Upon reaching failure, the permeabilities exhibited a marked increase, attaining values of $1.182 \times 10^{-14} \text{ m}^2$, $8.641 \times 10^{-14} \text{ m}^2$, and $7.106 \times 10^{-14} \text{ m}^2$, respectively. This represents an increase in permeability by factors of approximately 3.97, 3.21, and 3.61 relative to the initial measurements. Furthermore, the data indicate a trend whereby both initial and failure permeabilities decrease as the initial confining pressure increases.

Throughout the experimental procedure, the incremental increases in permeability at initial confining pressures of 10 MPa, 15 MPa, and 20 MPa were measured as $8.846 \times 10^{-15} \text{ m}^2$, $5.95 \times 10^{-15} \text{ m}^2$, and $5.137 \times 10^{-15} \text{ m}^2$, respectively. The data reveal a consistent decline in incremental permeability with increasing confining pressure. These findings confirm that elevated confining pressures inhibit the development of permeable pathways within the rock matrix, thereby reducing overall rock permeability.

During the unloading phase, tensile stresses develop radially within the specimen, causing the rapid initiation of internal cracks that serve as pathways for fluid flow, thereby increasing permeability. Throughout the subsequent creep phase, permeability gradually decreases with minor fluctuations before stabilizing at a relatively constant level. At

the final confining pressure stage, permeability shows significant fluctuations and an accelerated rate of increase, closely reflecting the observed strain evolution pattern [40].

Figure 10 illustrates the changes in permeability observed before and after the final creep stage. Experimental data show that, under an initial confining pressure of 10 MPa, permeability increases from $4.598 \times 10^{-15} \text{ m}^2$ immediately after unloading to $1.182 \times 10^{-15} \text{ m}^2$ during the final creep stage, representing a 157.07% increase. In contrast, the overall permeability increase before the final creep stage is limited to 54.61%. Similarly, at an initial confining pressure of 15 MPa, permeability rises from $4.134 \times 10^{-15} \text{ m}^2$ after unloading to $8.641 \times 10^{-15} \text{ m}^2$ during the final creep stage, corresponding to a 109.02% increase, whereas the cumulative increase before this stage is only 53.62%. Under an initial confining pressure of 20 MPa, permeability increases from $3.222 \times 10^{-15} \text{ m}^2$ post-unloading to $7.106 \times 10^{-15} \text{ m}^2$ during the final creep stage, amounting to a 120.55% increase, while the total increase before the final stage is 63.64%. These findings clearly demonstrate that the permeability augmentation during the final creep stage exceeds the combined increases observed in all preceding creep stages, indicating a marked acceleration in permeability during the specimen's accelerated creep phase. This phenomenon is primarily attributed to the specimen approaching failure under the highest confining pressure, which induces substantial volumetric strain, pronounced specimen dilation, extensive internal crack propagation, and the development of numerous fluid flow channels. Consequently, it can be inferred that permeability evolution during unloading creep is closely linked to the progression of axial, radial, and volumetric strains.

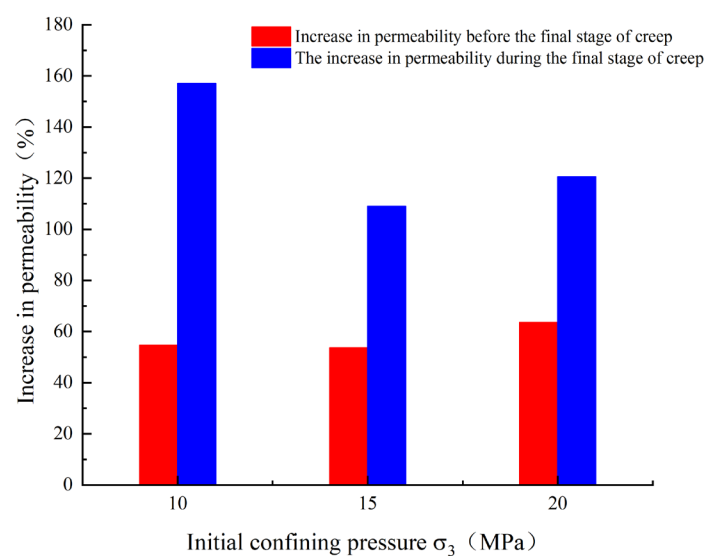


Figure 10. Increase law of rock permeability before and after the final creep stage.

3.4. Relationship Between Permeability and Strain

The analysis of the test results indicates that the progression of permeability and volumetric strain follows a similar developmental pattern, suggesting a clear correlation between these two parameters. Consequently, the relationship between permeability and volumetric strain during the unloading confining pressure creep test is examined. Figure 11 illustrates the temporal evolution of volumetric strain and permeability throughout each creep stage under three different initial confining pressure conditions.

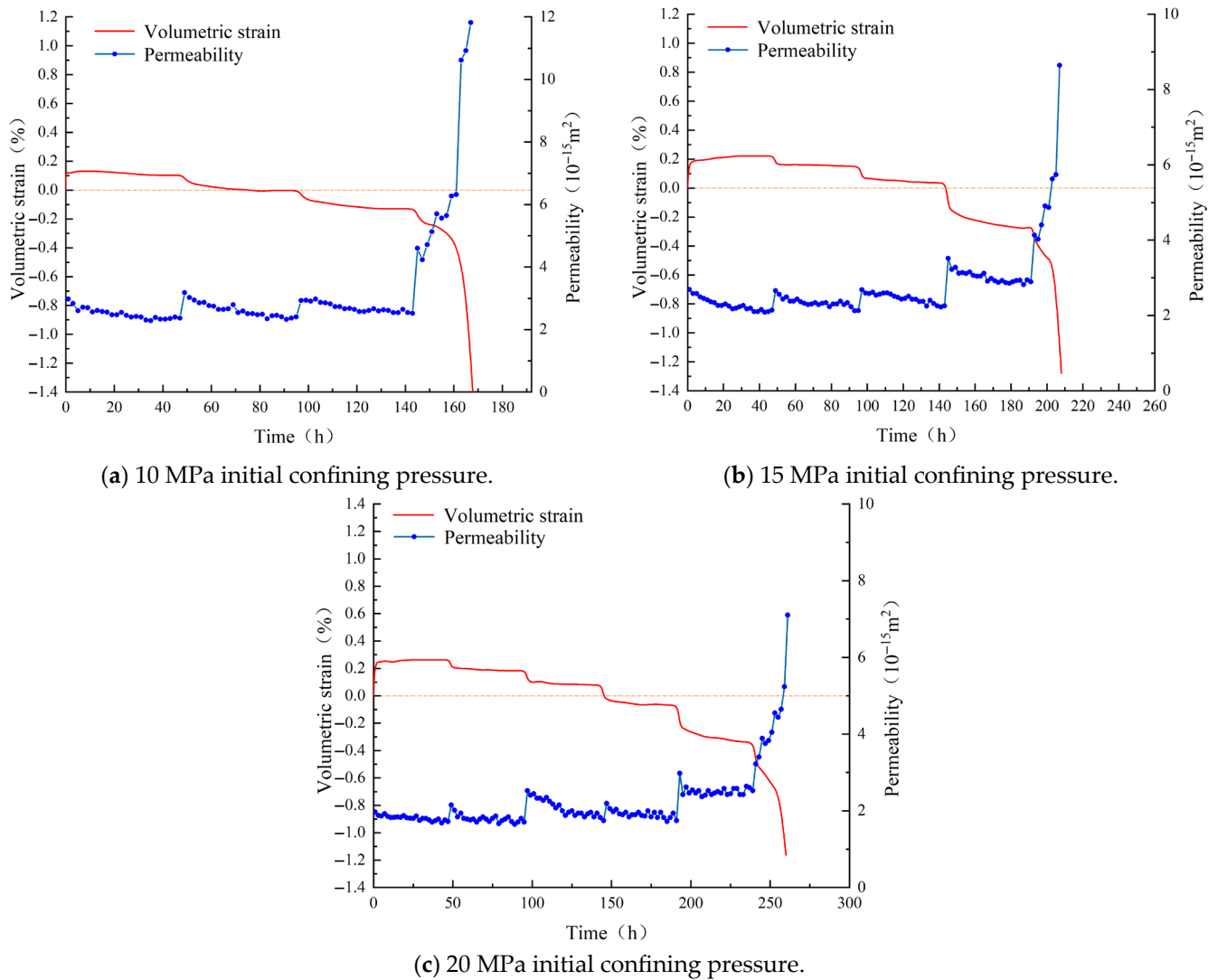


Figure 11. Evolution law of permeability and volumetric strain over time during the tests (the dashed line denotes the boundary where the volumetric strain value is zero): (a) relationship between permeability and volumetric strain under 10 MPa initial confining pressure; (b) relationship between permeability and volumetric strain under 15 MPa initial confining pressure; (c) relationship between permeability and volumetric strain under 20 MPa initial confining pressure.

The investigation demonstrates that the evolution patterns of average volumetric strain and permeability during the unloading process exhibit consistent characteristics. An increase in confining pressure corresponds to a decrease in the average permeability of rock specimens. Specifically, at an initial confining pressure of 10 MPa, the minimum and maximum average permeabilities within each creep stage are $2.503 \times 10^{-15} \text{ m}^2$ and $6.758 \times 10^{-15} \text{ m}^2$, respectively. When the initial confining pressure is raised to 15 MPa, these values decrease to a minimum of $2.288 \times 10^{-15} \text{ m}^2$ and a maximum of $5.293 \times 10^{-15} \text{ m}^2$. At an initial confining pressure of 20 MPa, the minimum and maximum average permeabilities further decline to $1.812 \times 10^{-15} \text{ m}^2$ and $4.375 \times 10^{-15} \text{ m}^2$, respectively.

Figure 12 illustrates the correlation between the mean volumetric strain and the average permeability observed during each phase of the creep process. Under a constant initial confining pressure, the specimen's volume undergoes slight compression during the early phase of testing, followed by gradual expansion. The volumetric strain progressively transitions from positive to negative values. While the volumetric strain remains positive, the specimen's internal permeability generally remains stable, exhibiting only minor in-

creases. This suggests minimal internal damage and limited development of permeable pathways. Once the volumetric strain becomes negative, its rate of increase typically accelerates significantly. Consequently, permeability begins to rise rapidly, culminating in pronounced specimen expansion accompanied by a sharp increase in permeability. This behavior primarily results from the inherent relationship between permeability and volumetric strain: the progressive evolution of volumetric strain induces expansion within the rock specimen, mainly due to the growth and widening of internal fractures [41]. These changes enable initially isolated fractures to connect, forming continuous channels that can conduct water. During the failure phase, many cracks quickly propagate and link together in a short period, resulting in a significant and rapid increase in the rock's permeability.

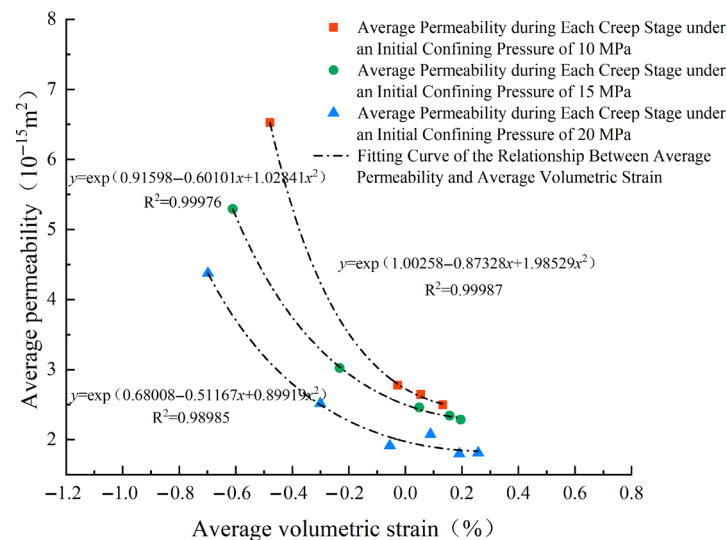


Figure 12. The relationship between average permeability and average volumetric strain under different initial confining pressures.

The analysis of the experimental data reveals a functional relationship between the average volumetric strain and the average permeability. This relationship is expressed by Equation (1), which was derived through data fitting procedures. Under varying initial confining pressure conditions, the correlation coefficient of the fitted function consistently exceeds 0.98, accurately characterizing the permeability evolution in response to volumetric strain during both the stable and accelerated creep stages.

$$k_a = e^{a_0 + b_0 \varepsilon_{va} + c_0 \varepsilon_{va}^2} \quad (1)$$

where k_a is the average permeability within each creep stage (m^2), ε_{va} is the average volumetric strain value within each creep stage, and a_0 , b_0 , c_0 are the fitting parameters.

3.5. Relationship Between Permeability and Confining Pressure

Figure 13 illustrates the correlation between average confining pressure and permeability across different creep stages observed in rock unloading creep experiments conducted at initial confining pressures of 10 MPa, 15 MPa, and 20 MPa. The experimental results indicate that, during the initial unloading phase, specimens subjected to higher confining pressures exhibit relatively minor changes in permeability, characterized by slight increases. However, once the confining pressure falls below a specific threshold, permeability undergoes a significant escalation [42].

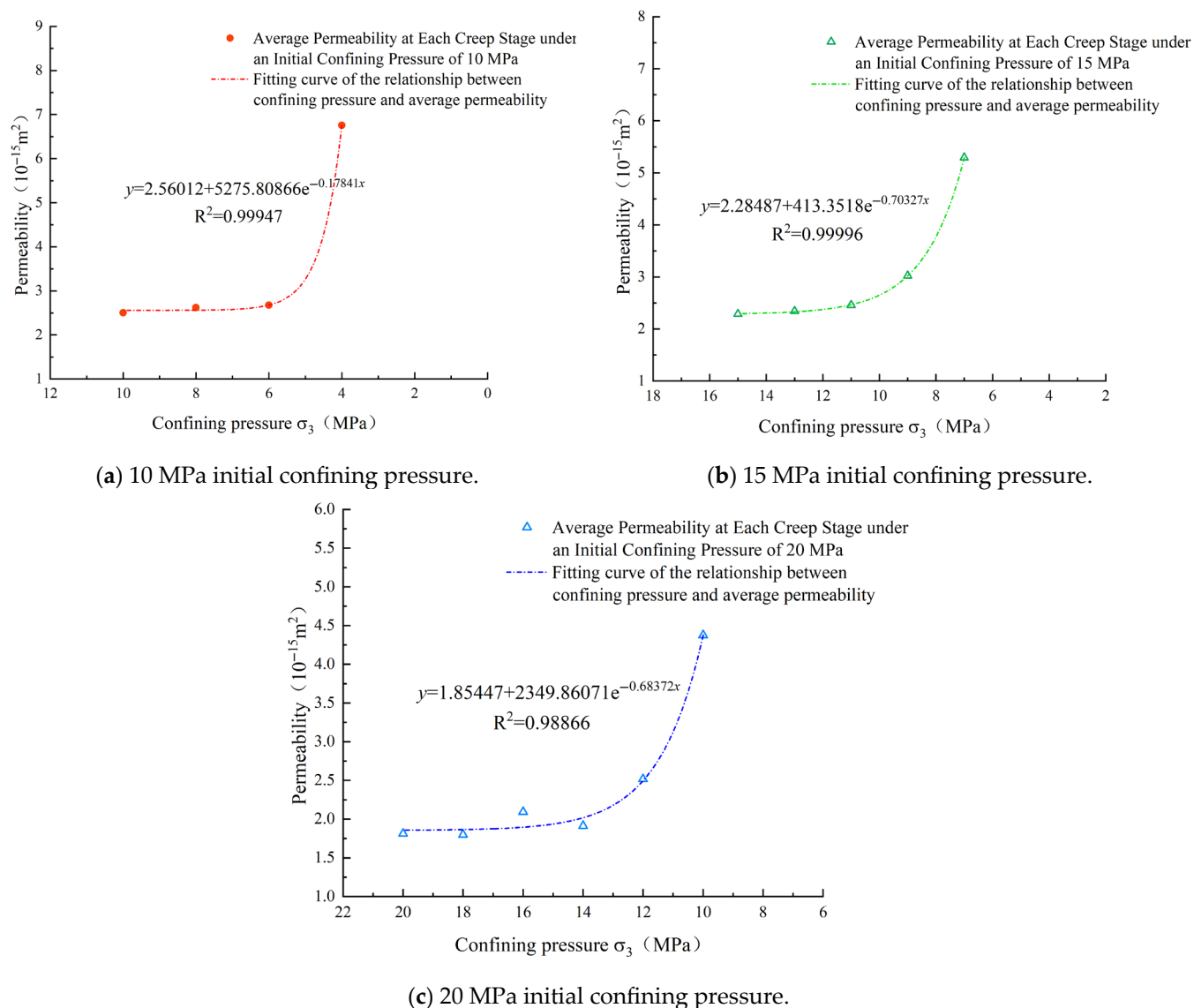


Figure 13. The relationship between average permeability and confining pressures under different initial confining pressures.

For instance, when the initial confining pressure was set at 10 MPa, unloading to 6 MPa resulted in an average permeability increase of $1.72 \times 10^{-16} \text{ m}^2$. Further unloading to 4 MPa induced the specimen to enter the accelerated creep phase, during which the permeability increased to $4.083 \times 10^{-15} \text{ m}^2$, representing a 23.74-fold enhancement compared to earlier creep stages. In the case where the initial confining pressure was 15 MPa, unloading to 9 MPa yielded an average permeability increase of $7.35 \times 10^{-16} \text{ m}^2$. Upon further unloading to 7 MPa, the specimen transitioned into the accelerated creep stage, with permeability increasing to $2.27 \times 10^{-15} \text{ m}^2$, approximately 3.09 times greater than that observed in preceding creep stages. Similarly, at an initial confining pressure of 20 MPa, unloading to 12 MPa produced an average permeability increase of $7.05 \times 10^{-16} \text{ m}^2$. Subsequent unloading to 10 MPa led the specimen into the accelerated creep phase, where permeability increased to $1.858 \times 10^{-15} \text{ m}^2$, corresponding to a 2.64-fold increase relative to earlier stages. These observations indicate that the average permeability of rock specimens at various confining pressure levels experienced a pronounced surge during the accelerated creep stage. Moreover, the experimental data demonstrate that as the initial confining pressure increases, the extent of permeability enhancement during the accelerated creep

phase progressively diminishes. This trend is primarily attributed to the fact that higher confining pressures constrain the expansion of internal fractures within the specimens.

The progression of average permeability in relation to confining pressure clearly demonstrates distinct stable and accelerated phases, which approximately follow an exponential model. The corresponding fitting formula is shown as follows:

$$k_a = a_1 + b_1 e^{c_1 \sigma_3} \quad (2)$$

where k_a is the average permeability within each creep stage (m^2), σ_3 is the current confining pressure (MPa), and a_1 , b_1 , and c_1 are the fitting parameters.

This research comprehensively examines the evolution of tuff permeability during the incremental unloading of confining pressure throughout the creep process. As the confining pressure is gradually reduced, the lateral constraint on the specimen decreases, while the deviatoric stress correspondingly increases. When the confining pressure falls below a critical threshold, the specimen approaches failure under the prevailing stress conditions, leading to extensive crack propagation within the rock matrix. Consequently, this results in a significant increase in permeability concurrent with strain progression during the accelerated creep phase.

4. Conclusions

This research investigates the creep behavior and permeability evolution of tuff under unloading confining pressure and coupled seepage–stress conditions. The results reveal that during the three distinct creep phases—instantaneous, steady state, and acceleration—radial strain predominates over axial strain. Additionally, this study identified that failure is characterized by volumetric expansion, with permeability showing a marked increase during the accelerated creep stage, exhibiting an exponential relationship with volumetric strain. The main conclusions are as follows:

- (1) A comprehensive experimental study on the creep behavior of tuff under the combined effects of seepage and stress was conducted, emphasizing how their interaction influences the rock's mechanical properties and permeability. The results reveal that the axial strain was initially greater than the radial strain; however, with each successive unloading step, the radial strain rate increased more rapidly. When the specimens failed, the radial strain exceeded the axial strain, indicating that rock failure under these conditions is mainly marked by significant radial expansion. For instance, under an initial confining pressure of 10 MPa, the radial strain was 1.24 times the axial strain at failure.
- (2) The progression of permeability is closely linked to the different stages of creep deformation. During the stable creep phases, permeability showed moderate and cumulative increases. Upon entering the accelerated creep phase, permeability increases significantly, exceeding the total permeability changes observed in all previous stages combined. This pattern suggests that extensive propagation and interconnection of internal microcracks, which create new flow pathways, mainly occur during the accelerated creep phase just before failure.
- (3) A strong quantitative correlation between permeability and volumetric strain was established. The analysis shows that permeability remains relatively constant when volumetric strain is positive, indicating compaction. In contrast, when volumetric strain becomes negative, signifying dilation, permeability increases exponentially. A high correlation function ($R^2 > 0.98$) was measured, establishing that the fitted curve accurately characterizes this relationship across both stable and accelerated creep stages, offering a reliable predictive model for permeability evolution based on deformation.

- (4) Confining pressure plays a fundamental role in controlling permeability. The relationship between average permeability and the confining pressure during each creep stage follows a decaying exponential trend. Additionally, higher initial confining pressures more effectively limit internal fracture expansion, leading to a progressively smaller increase in permeability during the accelerated creep phase. These findings highlight the crucial role of confining pressure in reducing damage evolution and its subsequent impact on hydraulic properties.

This study investigated the creep and seepage properties of tuff through triaxial unloading confining pressure creep tests conducted under coupled seepage–stress conditions. Due to certain limitations in the current research, several suggestions are proposed for future studies:

While this paper primarily focused on the macroscopic mechanical characteristics, creep behavior, and permeability characteristics of tuff during testing, it did not perform analyses at the microscopic level. The formation and expansion mechanisms of internal microcracks during rock failure are also critical for understanding the evolution of volumetric strain and permeability. Therefore, future research should include detailed microscopic examinations using techniques such as computed tomography (CT) scanning and scanning electron microscopy (SEM), as well as numerical simulation methods, to further enhance and complement this research.

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