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RESEARCH ARTICLE

Experimental Study on the Influence of Water-rock Interaction on the Mechanical Characteristics and Creep Behavior of Shale

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Abstract

In shale reservoirs, fracturing fluid can be easily absorbed into the pore space due to the strong capillary force of shale. These invading fluids can impact the rock mechanical properties and creep behavior characteristics of shale under water-rock interaction. This paper discussed the influence of water-rock interaction on the mechanical parameters and creep behavior of shale rocks based on shale hydration swelling experiments, acoustic-triaxial compression tests, and shale creep experiments. The experiments show that: There are two stages of shale hydration swelling: rapid swelling stage and stable swelling stage. Temperature mainly impacts the hydration swelling rate, while the type of liquid mainly impacts the hydration swelling amplitude. Water-rock interaction can damage the shale mechanical properties and cause the decrease of the Young's modulus, Poisson's ratio, and compressive strength. The degradation rate of Young's modulus and compressive strength significantly decreases after 10 days of water rock interaction. Water rock interaction can also alter the creep characteristics of shale, increasing the amplitude and rate of shale creep. The lower the liquid mineralization, the stronger the shale creep. The higher the temperature, the stronger the creep of shale.

Keywords: shale, water-rock interaction, rock mechanics parameters, shale creep, hydration swelling.

1 Introduction

Natural gas, as a clean energy source, has attracted significant attention for its efficient and rational development [1]. Compared to conventional gas reservoirs, shale reservoirs have micro-nano pores, strong capillary force and high clay content. Fracturing fluid can easily invaded into shale under the action of capillary force and pressure gradient. This process provides conditions for water-rock interaction in shale reservoirs. A series of physical and chemical reactions (such as shale hydration swelling, mechanical property degradation, shale creep, etc.) will occur and influence well production under the water-rock interaction. To analyze the influence of water rock interaction on

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shale hydration expansion, rock mechanics parameters, and creep characteristics, Various experimental studies have been conducted.

The hydration and expansion of shale has always been a hot topic of research and discussion. Numerous experiments on the hydration and expansion of shale under normal pressure have shown that the combination of water molecules and clay minerals in shale is the main factor leading to shale expansion [2]. There is a logarithmic increasing relationship between shale swelling rate and time. Tao et al. [3] analyzed the self-priming effect of shale with different clay contents through shale hydration infiltration experiments. Wang et al. [4] found that the higher the content of clay minerals, the easier hydration occurs, leading to more severe damage to shale structure and shorter time required for damage to occur. The degree of swelling varies in different liquid systems, and compared to deionized water, fracturing fluid has an inhibitory effect on hydration expansion. Meanwhile, some experimental studies have also shown that the degradation of shale mechanical properties by water rock interaction is quite significant [5]. Liu et al. [6] established the hydration index and hydration constitutive model of shale using spectra obtained from acoustic testing. Ma et al. [7] developed a constitutive model that can quantitatively describe shale hydration damage by combining CT scanning, which can be used to calculate the rock mechanics parameters after water-rock interaction. Lyu et al. [8] conducted core mechanics experiments on shale before and after immersion in fracturing fluid. Research shows that fluids have a significant impact on the mechanical properties of shale. Wang et al. [9] analyzed the effect of hydration under different confining pressures on shale structure and permeability. The evolution process of microcracks in shale during hydration is characterized by CT scanning technology. These research results indicate that the degradation of shale mechanical properties by water rock interaction may provide a possibility for the occurrence of water induced fracturing [10, 11]. Therefore, it is necessary to conduct an analysis of the degree of mechanical property degradation by the duration of water rock interaction, in order to provide a basis for determining the timing of water induced fracturing. The high mud content of shale also gives it strong time-dependent creep characteristics, which can impact the long-term conductivity of fractures and decrease the production of shale gas well [12]. In recent years, the creep behavior of shale has also become a research focus. Based on experimental results and simulation studies, many classic component models have been established to describe the creep behavior of shale [13–16]. With the introduction of fractional order theory, fractional order creep constitutive models have been widely used in the study of shale creep behavior due to their high fitting accuracy. However, there is currently more research on creep constitutive models, and less experimental research. The influence of water rock interaction, temperature, and liquid type on shale creep behavior is still unclear.

Based on shale hydration swelling experiments, acoustic-triaxial compression tests, and shale creep experiments, this paper discussed the influence of temperature, liquid type, and water-rock interaction time on hydration swelling rate, Young's modulus, Poisson's ratio, compressive strength, and shale creep curve. The challenge of not being able to reuse the same rock sample for multiple triaxial compression tests was addressed by combining acoustic testing with triaxial compression testing. Rock samples with similar mechanical properties were selected through acoustic tests and used to discuss the influence of water-rock interaction time on mechanical parameters. And the shale creep characteristics were analyzed based on the fractional Kelvin model, viscous modulus, and creep curve.

2 Experiment Scheme

2.1 Shale Hydration Swelling Experiments

Six sets of shale from Longmaxi Formation in Sichuan Province were used for hydration swelling experiments to discuss the impact of temperature, liquid type, and water-rock interaction time on hydration swelling rate. Table 1 shows the experiment scheme.

The hydration swelling ratio of shale sample in the experiment is

$$P = \frac{\Delta H}{H} \times 100\% \tag{1}$$

where P is hydration swelling ratio of shale sample, %; ΔH is swelling height of shale sample, mm; H is initial height of shale sample, mm.

2.2 Acoustic-triaxial Compression Test

Shale samples will be damaged directly during normal triaxial compression test and can not be reused for testing again. To overcome this limitation, Acoustic-triaxial compression test use acoustic wave

Table 1. Shale hydration swelling experiment scheme.

Experimental procedure	Sample	Liquid type	Temperature
1) Grind the shale to ≥ 100 mesh, weigh 20g of sample and place it in the testing cylinder.	P1	deionized water	20°C
2) Insert the plug rod into the test cylinder and apply uniform pressure to 10 MPa.	P2	2% KCl solution (simulate formation water)	20°C
3) Release pressure, remove the testing cylinder, measure the initial height H of the sample.	P3	Slick water fracturing fluid	20°C
4) Insert the induction valve stem into the test cylinder and reset the instrument dial to zero.	P4	deionized water	90°C
5) Inject liquid, apply pressure to 10 MPa, and record the swelling height of sample.	P5	2% KCl solution (simulate formation water)	90°C

Table 2. Acoustic-triaxial compression test scheme.

Experimental procedure	Sample	Liquid type
1) Dry the rock sample until the weight remains unchanged 2) Conduct rock acoustic testing to obtain dynamic Young's modulus and dynamic Poisson's ratio 3) Select rock samples for water-rock interaction experiments, with experimental times of 0d, 1d, 3d, 5d, 10d, and 20d, respectively 4) Conduct triaxial compression test	S1, S2, S3, S4, S5, S6	deionized water

to select shale samples with similar mechanical properties. The dynamic Young's modulus and dynamic Poisson's ratio are calculable using the compressional wave velocity and shear wave velocity from acoustic tests. Shale samples with similar dynamic Young's modulus and dynamic Poisson's ratio are considered to have comparable mechanical properties. These samples are used for water-rock interaction experiments and triaxial compression tests as shown in Table 2.

Based on acoustic testing results, the dynamic Young's modulus and dynamic Poisson's ratio of samples can be expressed as

$$\begin{cases} E = \dfrac{\rho c_s^2\left(3T^2-4\right)}{T^2-1} \\ \nu = \dfrac{T^2-2}{2\left(T^2-1\right)} \end{cases} \tag{2}$$

where T is the ratio of compressional wave velocity to shear wave velocity; c_s is the shear wave velocity, m/s; ρ is the density of rock, $\mathrm{kg/m^3}$.

2.3 Shale Creep Experiments

Shale samples are divided into two groups: a dry control group and a water-rock interaction group for analyzing the influence of water-rock interaction on shale creep behavior as shown in Table 3. The fractional Kelvin model is used to fit the creep strain-time curves and creep characteristic parameters are used to quantitatively describe shale creep.

The fractional order method is an effective method to describe time-dependent problem behaviors such as rock creep. Based on Kelvin model, the fractional Kelvin model was developed through introducing a viscous dashpot element. The constitutive equation is as follows:

$$\sigma = E_{2\nu}\varepsilon + \eta_2 D^{\zeta}\varepsilon \tag{3}$$

where σ is the stress, MPa; ε is the strain; $E_{2\nu}$ is viscosity modulus of shale, GPa; η_2 is fractional consistency coefficient; D^{ζ} is the differential operator of fractional order ζ; t is time, s; ζ is the fractional order.

The creep compliance of fractional Kelvin model can be obtained through Laplace transform:

$$J_k = \frac{1}{E_{2\nu}}\left[1 - E_{\zeta,1}\left(\frac{t}{\tau_2}\right)^{\zeta}\right] \tag{4}$$

$$E_{\zeta,1}(z) = \sum_{n=0}^{\infty}\frac{z^n}{\Gamma(\zeta n+1)} \tag{5}$$

where J_k is the creep compliance of fractional Kelvin model, $\mathrm{MPa^{-1}}$; τ_2 is fractional relaxation time, $\tau_2 =$

Table 3. Shale creep experiment scheme.

Experimental procedure	Sample	Liquid type	Temperature
1) Soak samples of the water-rock interaction group in liquid until the weight remains unchanged	R1	-	20℃
2) Seal samples with plastic and install sensors	R2	Deionized water	20℃
3) Zero the sensor, install hydraulic oil, steadily load 10MPa confining pressure, and control the ambient temperature to reach the set value	R3	Slick water fracturing fluid	20℃
4) Maintain the confining pressure, zero the sensor again, and load the axial pressure to the set value	R4	Deionized water	90℃
5) Maintain constant confining pressure and axial pressure, record shale strain	R5	Slick water fracturing fluid	90℃

$\frac{\eta_2}{E_{2\nu}}$; $E_{\zeta,1}$ is Mittag-Leffler special function; z is independent variable.

3 Experimental Results and Discussion

3.1 The Influence of Water-Rock Interaction on Shale Hydration Swelling

Table 4 shows the swelling stage change time and hydration swelling ratio of shale samples.

Figure 1 shows hydration swelling ratio of shale in different liquids at 20℃. The experimental results indicate that the liquid type and water-rock interaction time significantly impact the degree of shale hydration swelling. The hydration swelling ratio of shale gradually increases with the increase of reaction time, while the increase rate gradually decreases. The process of hydration swelling can be divided into two stages: rapid swelling stage and stable swelling stage. There are significant differences in the swelling stage change time of samples P1, P2, and P3. The maximum hydration swelling ratio of P1, P2, and P3 are 1.86%, 1.36%, and 0.38%, respectively. The swelling stage change time of P1, P2, and P3 are 780min, 980min, and 1200min, respectively. The experimental results of these three samples evident that the hydration swelling ratio of shale decreases with the increase of mineralization degree, which the swelling stage change time is positively correlated with mineralization degree. The mineralization degree of liquids has a significant impact on the hydration swelling rate and amplitude.

Figure 2 shows the experimental results of hydraulic swelling in different liquids at 90℃. Comparing the results in Figures 1 and 2, it can be concluded that the hydration swelling of shale still shows a two-stage characteristic at high temperatures. But the swelling stage change time is shortened by 25-30 times when the temperature rises from 20℃ to 90℃. The swelling stage change time of P4, P5, and P6 are 32min, 31min, and 38min, respectively. The maximum hydration swelling ratio of P4, P5, and P6 are 1.89%, 1.41%, and 0.42%, respectively. It can be concluded that temperature has a significant impact on the hydration swelling rate.At high temperatures, the reaction rate between water molecules and clay minerals will increase and hydration swelling can be promoted. But

Table 4. Shale hydration swelling experiment scheme.

Sample	Experimental condition	The swelling stage change time (min)	Hydration swelling ratio (%)
P1	20℃, deionized water	780	1.86
P2	20℃, 2% KCl solution	980	1.36
P3	20℃, Slick water fracturing fluid	1200	0.38
P4	90℃, deionized water	32	1.89
P5	90℃, 2% KCl solution	31	1.41

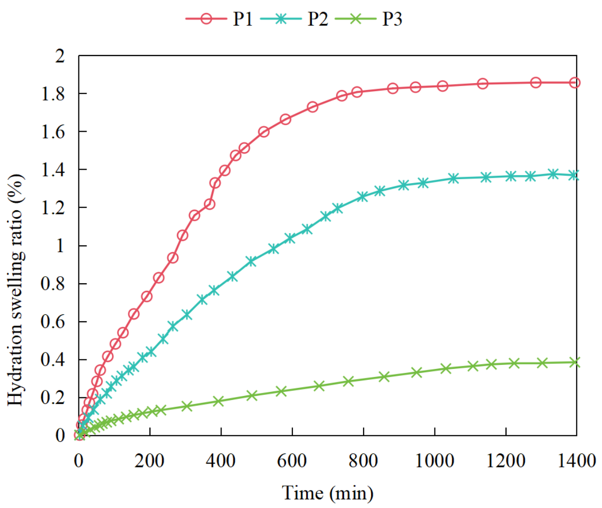

Figure 1. The hydration swelling ratio of shale in different liquids at 20°C.

the temperature has little impact on the hydration swelling amplitude.

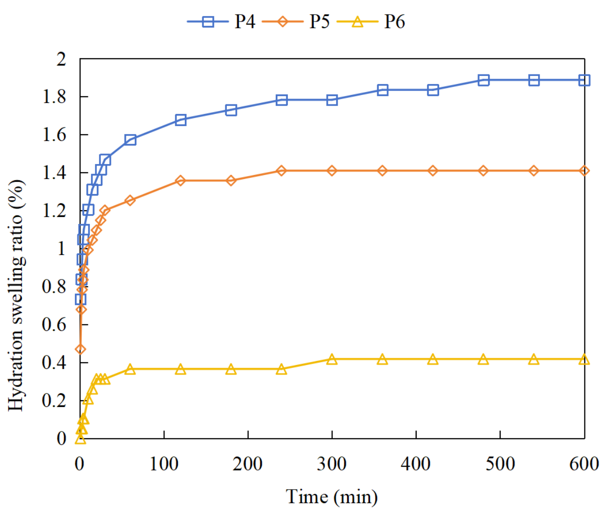

Figure 2. The hydration swelling ratio of shale in different liquids at 90°C.

During the hydraulic fracturing construction, The temperature of rocks around hydraulic fractures will decrease due to contact with fracturing fluid. The hydration swelling rate is low in this period. During shut-in period, the hydration swelling rate in the SRV area will significantly increase as temperature gradually increases.

3.2 The Influence of Water-Rock Interaction on Shale Mechanical Parameters

Table 5 and Figure 3 show the dynamic Young's modulus and dynamic Poisson's ratio of shale samples from acoustic tests. The average dynamic Young's modulus and dynamic Poisson's ratio of the 6 selected rock samples is approximately 45GPa and 0.15, respectively. The mechanical properties of the 6 rock samples are similar.

Table 5. The dynamic Young's modulus and dynamic Poisson's ratio of shale samples.

Sample	Dynamic Young's modulus (GPa)	Dynamic Poisson's ratio
S1	44.95	0.1476
S2	43.45	0.1608
S3	45.52	0.1494
S4	43.79	0.1664
S5	47.55	0.1532
S6	45.22	0.1539

Samples S1 S6 are soaked in deionized water for 0d, 1d, 3d, 5d, 10d, and 20d, respectively. The Young's modulus, Poisson's ratio, and compressive strength under different water-rock interaction times are obtained through triaxial compression experiments. The results are showed in Table 6 and Figure 4.

Table 6. The results of triaxial compression experiments.

Sample	Water rock interaction time (d)	Young's modulus (GPa)	Poisson's ratio	Compressive strength (MPa)
S1	0	35.87	0.18	261.0
S2	1	34.07	0.17	235.8
S3	3	33.06	0.16	222.8
S4	5	29.81	0.17	234.3
S5	10	28.02	0.17	177.0
S6	20	25.08	0.16	160.9

The results of the triaxial compression experiment in Figure 4 indicate that water-rock interaction can alter the mechanical properties of shale, and the water-rock interaction time has a significant impact on the stress-strain curve, Young's modulus, Poisson's ratio, and compressive strength of shale. As the water-rock interaction time increases, the Young's modulus and compressive strength of shale gradually decrease, but the decrease rate gradually drops. After 10 days of water-rock interaction, the change amplitude of Young's modulus and compressive strength significantly decreases. No distinct pattern was observed in the variation of shale Poisson's ratio with water-rock interaction time, though an overall negative correlation is suggested. These results indicate that the shale mechanical properties is damaged significantly during the initial stages of water-rock interaction. After 10 days of interaction, the rate of mechanical parameter degradation diminishes. The damage process of shale mechanical properties provides conditions for enhancing permeability during shut-in period in shale gas reservoirs.

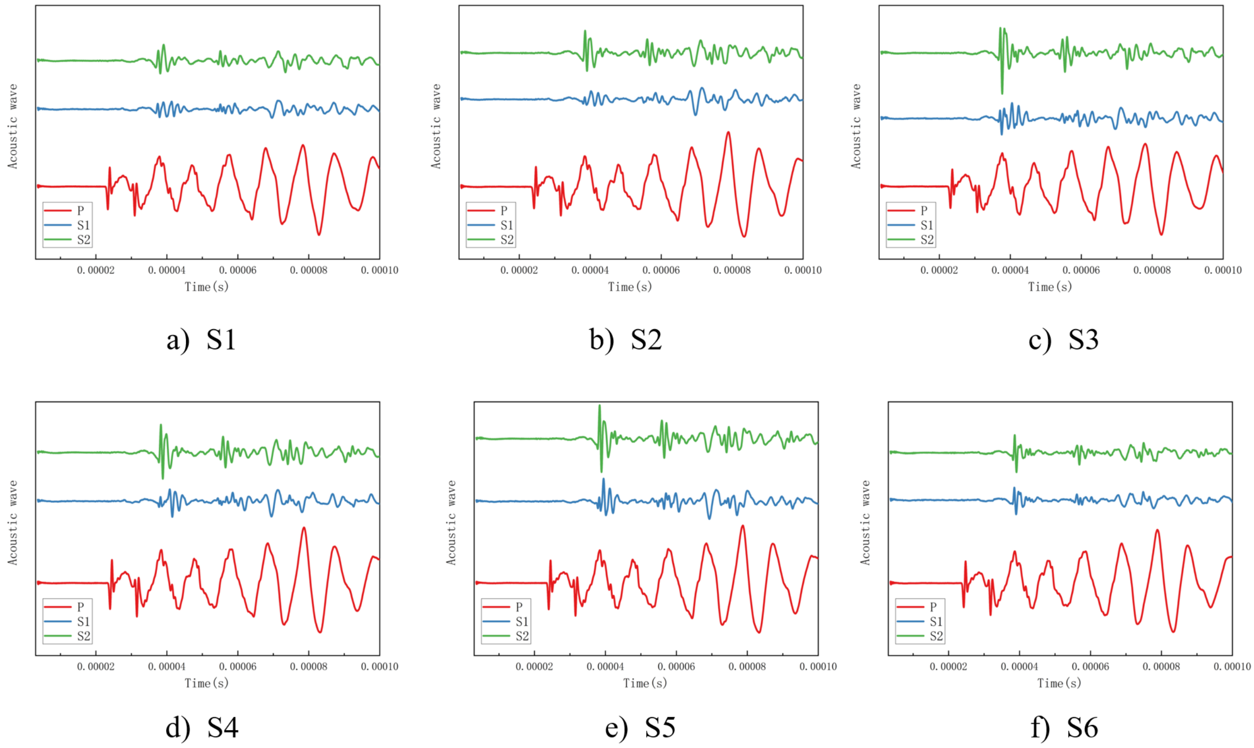

Figure 3. The results of acoustic tests.

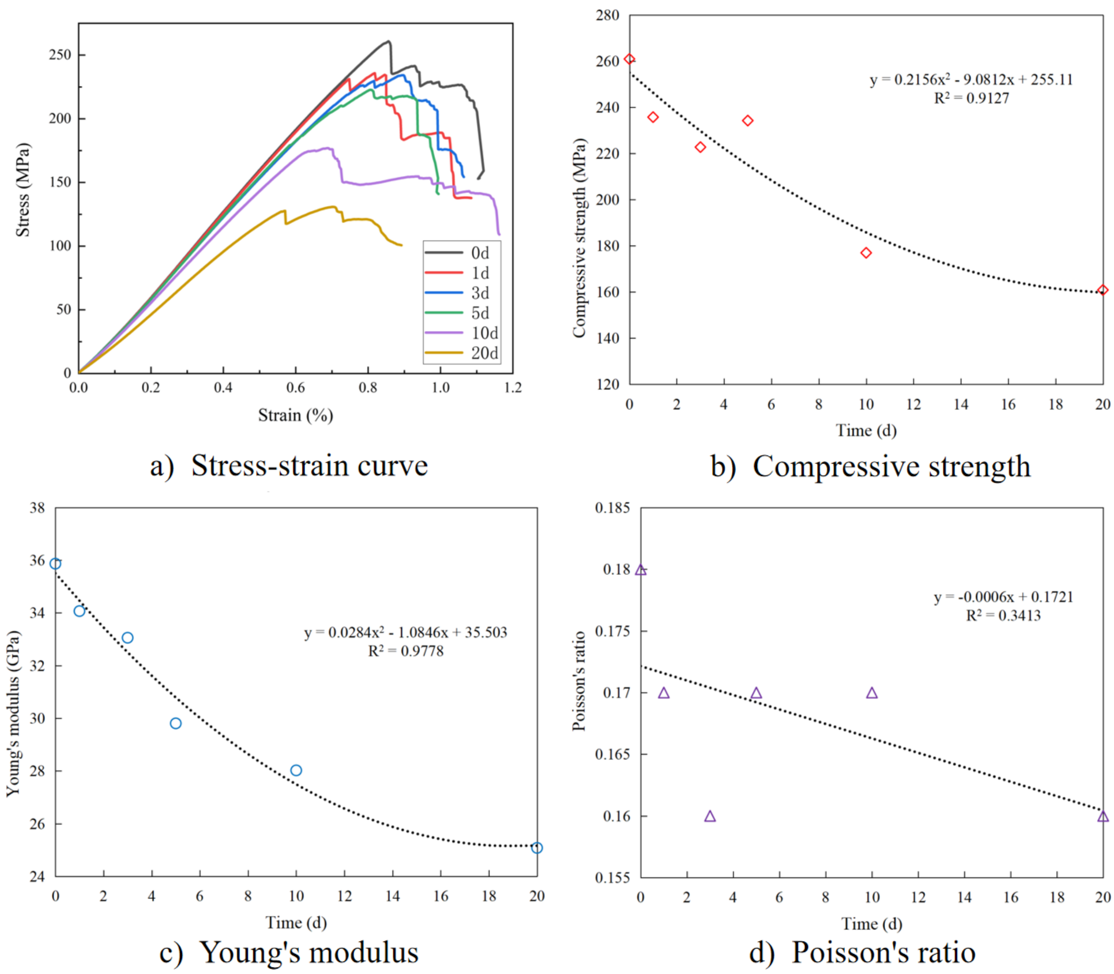

Figure 4. Triaxial compression test results under different water-rock interaction times.

Table 7. The fitting results of shale creep experiment.

Sample	Experimental condition	$E_{2\nu}$ (GPa)	ζ	τ_2	R^2
R1	Dry sample	72.94	0.4522	7.056	0.9965
R2	20°C, deionized water	21.79	0.2968	11.07	0.9767
R3	20°C, Slick water fracturing fluid	36.75	0.3766	6.298	0.9207
R4	90°C, deionized water	1.35	0.1978	196.8	0.9907
R5	90°C, Slick water fracturing fluid	2.29	0.1729	106.3	0.9814

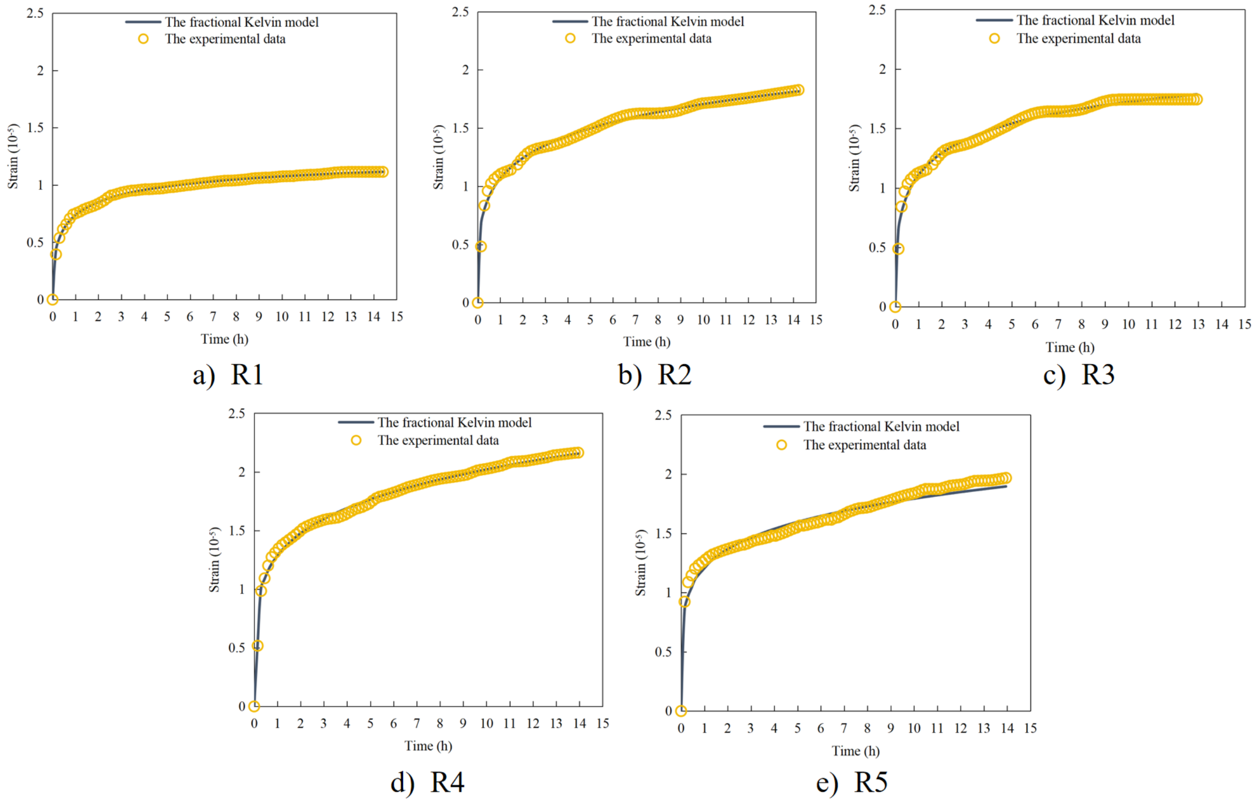

Figure 5. Strain-time curves of creep and fitting curves of fractional Kelvin model.

3.3 The Influence of Water-rock Interaction on Shale Creep Behavior

The experimental results of shale creep and the fitting results of the fractional Kelvin model are shown in Table 7 and Figure 5. The fitting results indicated that the fractional Kelvin model has a high fitting accuracy for the strain time curve of shale creep experiments, and can accurately describe the creep behavior of shale. Figure 5 shows that the stress-strain curve of shale creep exhibits a two-stage characteristic of rapid creep stage and slow creep stage. The creep strain of shale gradually increases with the increase of experimental time, but the increase rate of creep strain gradually decreases. The creep strain rate of dry sample R1 exhibits a significant inflection point, beyond which the strain stabilizes and the increase rate markedly decreases. The water-rock interacted sample demonstrates sustained creep strain progression at a measurable rate after the initial rapid creep phase, with significantly higher cumulative strain than dry sample R1. This pattern indicates that water-rock interaction substantially influences both the magnitude and characteristics of shale creep, enhancing both creep rate and total creep strain.

The viscous modulus (E_{2v}) obtained by fitting the fractional Kelvin model can be used to characterize the ability of rock samples to resist creep. Based on the fitting results and creep strain-time curve, it can be concluded that the viscosity modulus of dry rock sample R1 is significantly higher than that of other rock samples, while the creep strain is the smallest. The creep stress of rock samples R2 and R4 in deionized water environment is greater compared to the rock samples R3 and R5 under the action of fracturing fluid, and the viscosity modulus is smaller. This phenomenon indicates that the liquid environment of water rock interaction will impact the creep of shale, and the lower the liquid mineralization, the greater the creep strain of shale and the smaller the viscous modulus. By comparing the creep strain and viscous modulus under the same liquid environment and different reaction temperatures, it is found that the higher the temperature, the greater the creep strain and the smaller the viscous modulus.

The water rock interaction, reaction liquid type, and temperature are the main factors impacting shale creep. Water rock interaction can promote shale creep, increase the amplitude and rate of shale creep; The lower the liquid mineralization, the stronger the shale creep, and the higher the temperature, the stronger the shale creep.

4 Conclusion

(1) The hydration swelling of shale involves two stages: rapid swelling stage and stable swelling stage. Temperature and liquid type are the main factors affecting the hydration expansion of shale. Temperature mainly influences the hydration swelling rate, while liquid type influences the hydration swelling amplitude. The increase in temperature will accelerate the swelling of shale, leading to an earlier change in the swelling stage, but the impact of temperature increase on the hydration swelling amplitude of shale after stable expansion is relatively small. The higher the liquid mineralization degree of water rock interaction, the smaller the amplitude and rate of shale hydration swelling.

(2) The water rock interaction has a significant impact on the stress-strain curve, Young's modulus, Poisson's ratio, and compressive strength of shale. As the time of water rock interaction increases, the Young's modulus and compressive strength of shale gradually decrease, but the magnitude of the decrease gradually decreases. The change in Poisson's ratio exhibits significant fluctuations, but overall it also shows a downward trend. The early stage of water rock interaction has a significant degradation effect on the mechanical properties of shale rocks, and after 10 days of water rock interaction, the degradation amplitude of mechanical parameters weakens.

(3) The strain-time curve of rock creep exhibits a two-stage characteristic of rapid creep stage and slow creep stage. The fractional Kelvin model has a high fitting accuracy for the strain-time curve of shale creep experiments and is suitable for describing the creep behavior of shale. Water rock interaction, liquid type, and temperature are the main factors affecting shale creep. Water rock interaction can promote shale creep, increase the amplitude and rate of shale creep; The lower the liquid mineralization, the stronger the shale creep, and the higher the temperature, the stronger the shale creep.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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