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Experimental Investigation on the Effects of Ambient Freeze–Thaw Cycling on Creep Mechanical Properties of Sandstone Under Step Loading

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ABSTRACT In order to study the creep mechanical properties of sandstone subjected to graded loading under the condition of freeze-thaw cycles, 15 freeze–thaw cycles were conducted with four groups of rock samples. The porosity variation of sandstone before and after the freeze–thaw cycles were obtained by using the nuclear magnetic resonance (NMR) technique. The results show that under the action of freeze–thaw cycles, the cohesion between particles inside the rock decreases, the pore structure deteriorates continuously, and the porosity of the rocks increases. During the graded loading creep test, the rock underwent macroscopic failure under low-level loading. Moreover, the fracture morphology showed tensile-shear failure characteristics, which caused obvious decreases in the long-term strength of the rock. The comprehensive analysis of the experimental data to establish the creep model and constitutive equation under the condition of the freeze-thaw cycle, and discuss the relationship between creep model parameters and freeze-thaw factors. The nonlinear creep mode can effectively reflect the graded loading creep law of frozen and thawed sandstone.

INDEX TERMS Constitutive model, creep characteristics, freeze–thaw cycle, mesoscopic damage law.

I. INTRODUCTION

Freezing and thawing is a natural phenomenon commonly encountered in mines and geotechnical engineering in cold regions. Under the effects of freeze–thaw cycles, the rock mass is damaged, which will easily lead to freeze–thaw denudation and sliding [1]. In cold environments, in addition to the freezing and thawing effects, the geotechnical components also include initial stress, gravity, and external loading for long periods. Under such conditions, the stress and deformation characteristics will change slowly with changes in time. Thus, these rock time-dependent characteristics directly cause instability and damage to the rock mass [2], [3]; therefore, mastering the creep deformation law can effectively reflect the time-dependent characteristics. Accordingly, studying the rock creep mechanical properties can help to reveal the long-term stability mechanism of geotechnical engineering in cold regions.

Previous research of rock creep mechanical characteristics has been conducted through indoor experiments, theoretical derivation, numerical calculations [4], [5], and other methods. Griggs [6] first performed uniaxial compression creep tests on soft rocks such as limestone, shale, and siltstone, pointing out that when the load reaches 12.5%–80% of the failure load, creep occurs in sandstone, mudstone, and siltstone. Zhao et al. [7] conducted tests including uniaxial compression and graded loading creep of red sandstone. They found that the failure mode of rock includes axial multi-crack splitting and local tensile failure. In addition, they investigated the transient loading strain, attenuation strain, steady-state strain, and acceleration strain. Kinoshita and Inada [8] studied the effect of temperature on rock creep properties, showing that the long-term strength decreases with an increase in temperature. In the creep model, four basic

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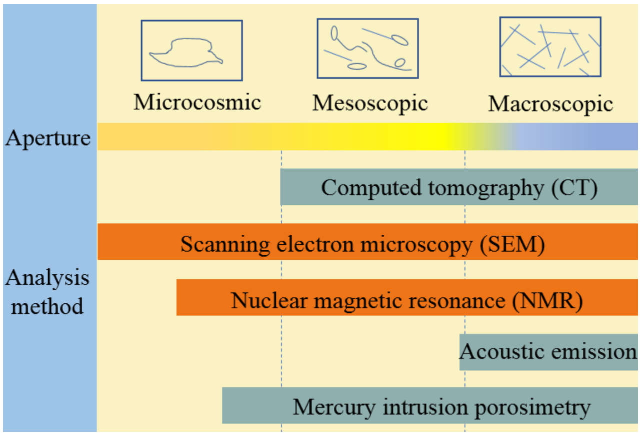

FIGURE 1. Different damage scales and recognition means of the rock.

rheological models include viscoelastic, elasto-viscoplastic, viscous, and viscoplastic are generally used to describe the creep process of rocks with different properties [9]–[11]. Owing to the nonlinear behavior of rock creep, many new nonlinear creep models have been proposed on the basis of the unified creep model. These include the nonlinear viscoplastic model considering the accelerated rheological properties [12], the classical combination model considering aging damage [13], the transient thermal damage variable and creep constitutive model considering the temperature effect [14], as well as the creep damage model of seepage–stress coupling [15].

Numerous geological defects such as micro-fractures and micro-cavities inside the rock affect the mechanical, physical, and chemical properties of the geotechnical materials [16]. In addition, changes in the pore structure and distribution characteristics create differences in the rock creep mechanical properties [17]–[20]. At present, mercury intrusion porosimetry, X-ray computed tomography (CT), scanning electron microscopy (SEM), nuclear magnetic resonance (NMR), acoustic emission (AE), and other technical methods are used to study the mesoporous structure of frozen and thawed rocks. NMR is a nondestructive, easy, and less time-consuming technology which covers the widest aperture range. And SEM can observe the surface morphology of rock samples, which is used to analyze the rock failure characteristics (Fig 1). For example, Li *et al.* [21] conducted NMR tests on granite with different freeze–thaw cycles by analyzing the internal microstructure distribution and damage process of the same rock sample after different freeze–thaw cycles. The results showed that the porosity and T_2 spectral area increased with an increase in the number of freeze–thaw cycles. Liu *et al.* [22] reconstructed the three-dimensional structural image of rock by using CT. They studied the shape and spatial distribution of internal cracking and its development process during pore water freezing. Zhai *et al.* [23] used NMR and SEM to analyze the effects of freeze–thaw on the permeability of coal samples. They found that multiple freeze–thaw cycles enabled the internal pores of the coal sample to continuously and expand to form a network of interlaced fractures and enhanced coal seam permeability.

TABLE 1. Sandstone mineral composition.

Mineral composition	Iron serpentine	Talc	Kaolinite	Feldspar	Quartz
Percent	2.2	1.2	1.3	0.9	94.4

At present, research on the mechanical properties and damage mechanism of freeze–thawed rocks contains little information on the damage caused by freeze–thaw and long-term loading. In this study, the authors use sandstone as samples to analyze the changes in the rock meso-structure before and after the freeze–thaw cycle based on NMR detection. Then, a rock uniaxial compression creep test and fracture morphology SEM testing are conducted to obtain the creep damage characteristics of the freeze–thawed rock. According to the test results, the improved nonlinear creep model is used for parameter identification and verification to reveal the damage law of the freeze–thaw cycle on the long-term strength.

II. EXPERIMENTAL

A. ROCK SPECIMENS

The rock sample was yellow sandstone taken from the Gannan area of Gansu Province, China. This sample has strong homogeneity and integrity and is composed mainly of cemented sand. The sandstone gravel is ground into fine particles of less than 10 using a mortar, and subject to X-ray fluorescence spectrometry (XRF). The mineral composition of the selected sandstone is shown in Table 1. The mineral composition of the sandstone is mainly quartz, accounting for 94.4%, and clay minerals such as iron serpentine, talc, kaolinite, and feldspar accounting for 5.6%.

B. EXPERIMENTAL PROCEDURE

The experimental system and equipment include mainly four steps: a freeze–thaw cycle experiment, NMR test, uniaxial compression graded loading creep test, and fracture morphology scanning. The specific experimental flow is shown in Fig. 2.

1) FREEZE–THAW CYCLE

The rock samples were immersed in distilled water for vacuum saturation, and the freeze–thaw cycle experiment was then completed by using a freeze–thaw cycle machine (TDS-300). According to the climatic conditions of the sampling site, the freezing temperature was −10 °C, the thawing temperature was 20 °C, and the freezing and thawing periods were each 4 h; that is, each freeze–thaw cycle was 8 h. A testing cycle included five freeze−thaw cycles. After each testing cycle, the rock samples were removed to observe changes in their characteristics. In addition, NMR testing was conducted to determine the changes in porosity before and

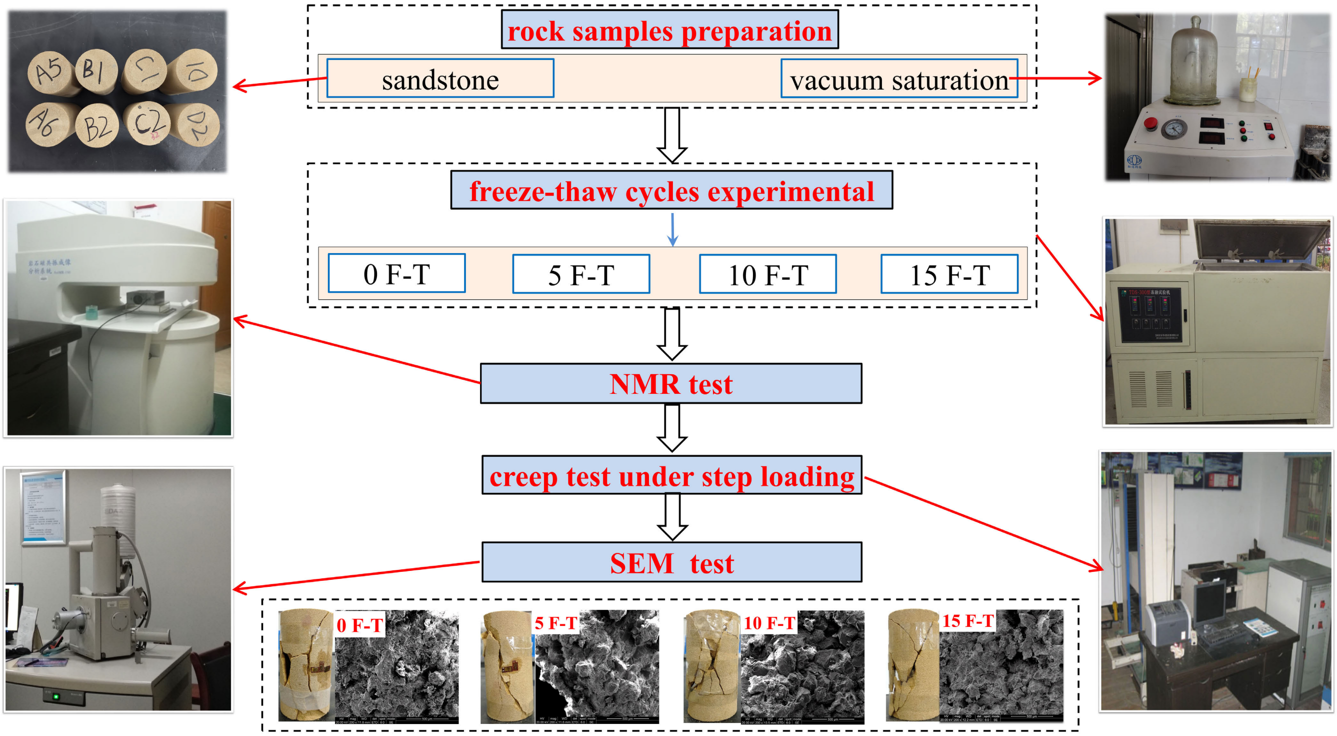

FIGURE 2. Experimental flow chart.

TABLE 2. Stress–strain table for graded loading creep of sandstone under freezing and thawing conditions.

Freeze–thaw cycles/times		Axial creep strain under different graded loading stress (kN)/%							
		24.85	33.14	41.42	49.7	57.99	66.27	74.56	total strain/%
0	Loading section	1.503	0.131	0.129	0.106	0.098	0.098	0.088	2.40
	Creep section	0.040	0.028	0.021	0.029	0.030	0.023	0.030	
5	Loading section	1.465	0.134	0.121	0.107	0.098	0.088	0.084	2.30
	Creep section	0.024	0.029	0.029	0.028	0.029	0.034	0.034	
10	Loading section	1.486	0.14	0.123	0.106	0.097	0.096		2.34
	Creep section	0.029	0.029	0.032	0.037	0.071	0.091		
15	Loading section	1.394	0.136	0.089	0.107	0.098	0.096		2.36
	Creep section	0.049	0.038	0.024	0.031	0.042	0.224		

after each rock freeze–thaw cycle. This procedure continued until 15 freeze–thaw cycles were completed.

2) CREEP TEST UNDER STEP LOADING

The rock samples were first subjected to uniaxial compression testing; the average compressive strength was determined to be 43.93 MPa. The creep loading method adopted the ''Chen's loading method'', and the total load was predicted according to the uniaxial compressive strength of the rock specimens, and the creep test were carried out at 5-6 stress levels. So, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the average value of the rock uniaxial compressive strength were taken as stress grades of the step loading test by using a rock shear rheometer (RYL-600) respectively. The loading rate per stage was 100 N/s. When the creep strain increment of this stage was less than 0.001 mm/h [24], the rock was considered to have entered the stable creep state. Afterward, the stress loading of the next stage was performed until the full-grade loading test was completed.

3) SEM FRACTURE MORPHOLOGY

After creep damage occurred, fractures in the rock fragments were scanned by using environmental SEM (Quanta-200) to obtain the meso-structure characteristics.

III. RESULTS AND DISCUSSION

A. CREEP DEFORMATION CHARACTERISTICS OF SANDSTONE UNDER THE CONDITION OF FREEZE–THAW CYCLES

Table 2 shows the creep strain and stress changes in the sandstone under freeze–thaw action. For graded load rock, the strain of the first stage load accounted for about 65% of the total strain. As the load increased, the strain of the rock loading section gradually decreased, and the average value was reduced from 0.14% to 0.09%. Although the strain of

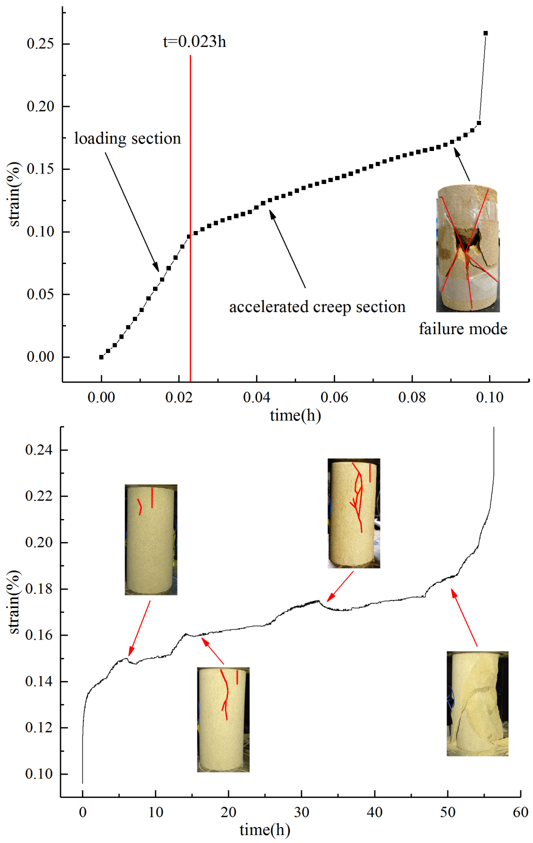

FIGURE 3. **Rock creep failure mode diagram: (a) brittle failure; (b) ductile-brittle failure.**

the rock creeping section tended to increase gradually until the accelerated creep stage occurred, the creep strain of the rock increased significantly. During the staged loading process, the pores inside the rock were continuously compacted, and the deformation continued to increase until macroscopic damage occurred. For rocks subjected to zero or five freeze–thaw cycles, the seventh-stage load entered a stable creep state, which was maintained under the constant load. The rock that experienced 10 or 15 freeze–thaw cycles entered the accelerated creep state under the sixth-stage load. After a period of continuous loading, the rock produced macroscopic damage. The data in Table 2 show that the strain mean values of the graded loading creep sections of different freeze–thaw cycles were 0.027%, 0.031%, 0.033%, and 0.034%, showing an increasing trend. Under the same loading series, the rock total strain increased with an increase in the number of freeze–thaw cycles. Therefore, the rock reached its deformation limit under a lower load, which caused macroscopic damage, and a gradual decrease in the long-term strength of the rock.

B. MACROSCOPIC FAILURE MODE OF ROCK UNDER GRADING LOADING

Rock lithology, freeze–thaw cycle temperature, freeze–thaw cycles and other factors will lead to differences in long-term strength of rock [25], [26]. In the uniaxial compression grading loading creep test, as the grading load increased step by step, the rock state changed from stable creep to accelerated creep. When the loading reached the accelerated creep state, the rock exhibited different failure modes. As shown in Fig. 3, the accelerated creep failure mode can be divided into two cases. In the first, the creep deformation speed of the rock is short and rapid, showing a characteristic similar to linear growth. The rock quickly undergoes macroscopic damage as typical brittle failure (Fig. 3(a)). In the second case, the rock maintains a uniform rate of creep deformation, and fine cracks first appear on the surface in an axial direction. As the loading time increases, the number and length of the cracks increase continuously. Single cracks continue to expand and to extend, and some of the cuttings and fragments fall onto the surface. The degree of rock damage continues to increase until conjugate shear failure and local tensile failure occur (Fig. 3(b)). Thus, when the rock's graded loading stress reaches or exceeds its long-term strength, the rock will produce shear failure. Regardless of the type of rock deformation mode in the staged loading process.

According to the rock strain variation law illustrated in Fig. 3(b), the axial strain of rock decreases locally with the development of macroscopic cracks in the accelerated creep stage. This indicates that the constant load causes the internal particle structure to continuously become damaged, and the relative displacement between the particles increases. When the displacement reaches a certain level, the rock sample undergoes partial plastic failure, which releases part of the accumulated internal stress. This causes the creep time–strain curve to decrease locally.

C. MESOSCOPIC DAMAGE LAW OF FREEZE–THAW ROCKS

Under the action of freeze–thaw cycles, the water–rock phase transformation of the internal pores and micro-fracture water produces frost heaving pressure [27], which makes the internal pores expand and develop along the weak structural plane. When the temperature rises and the ice melts into water, the water gradually migrates into the newly formed micro-fractures and pores. This generates greater frost heaving pressure at the next freeze, causing the rock to be damaged during the freeze–thaw cycles [28], [29]. For the rock samples subjected to zero, 5, 10, and 15 freeze–thaw cycles, the porosity increased 11.0%, 12.3%, 13.5%, and 14.3% respectively, compared with 11.8%, 22.7%, and 30% prior to the cycles. Therefore, it can be explained that under the long-term action of the freeze-thaw cycles and loads, the pore structure inside the rock is degraded by continuous damage. Under constant long-term load, the freezing and thawing will accelerate the rock damage rate and cause the rock macroscopic damage earlier.

The mineral composition of the rock also has an important impact on freeze–thaw damage. As shown in Table 1, the sandstone samples contain clay minerals that undergo water absorption, expandability, and shrinkage [30]. Under the action of freezing and thawing, the clay particles swell and deform as well as freeze and loosen. This causes the cohesive

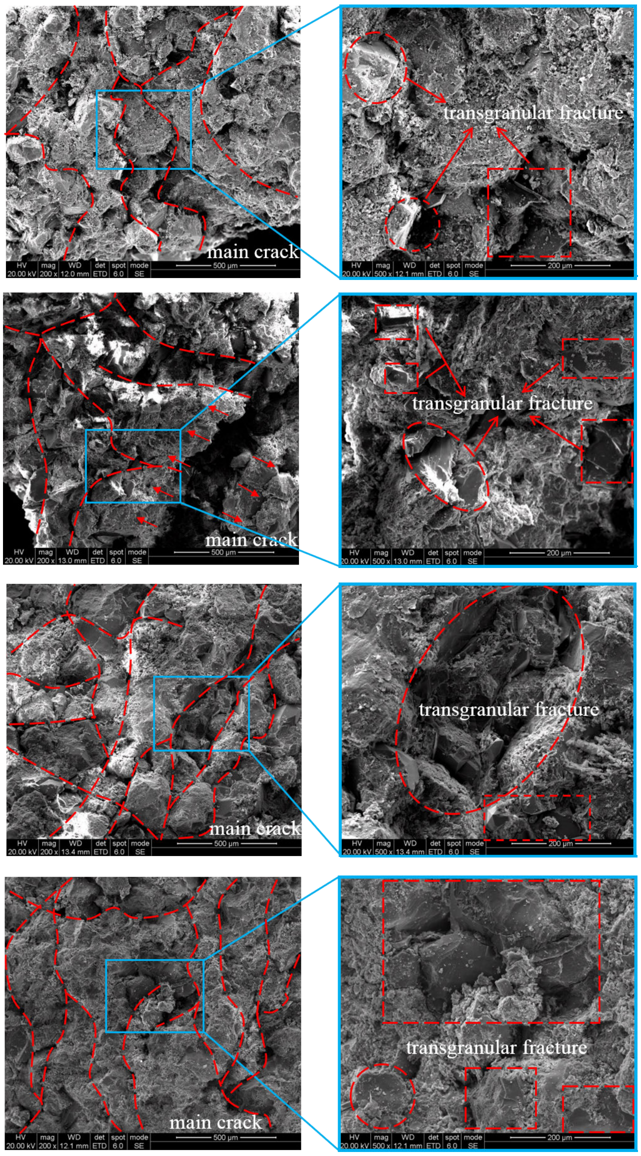

FIGURE 4. Rock fracture image of (a) zero, (b) 5, (c) 10, and (d) 15 freeze–thaw cycles.

force between the particles inside the rock to decrease, so that the pore structure is more easily expanded and is developed under the action of frost heaving pressure. Therefore, in the staged loading process, quartz crystals are more brittle and less prone to viscoplastic deformation, resulting in macroscopic tensile shear failure of the rock.

The SEM images of the rock fracture morphology with different freeze–thaw cycles are shown in Fig. 4. The fracture surface is composed mainly of massive quartz crystals with clay minerals attached to the surface. With an increase in the number of freeze–thaw cycles, the cracks on the rock fracture surface develop rapidly. In addition, the cemented minerals between the particles dissolve and are destroyed, forming a dense network of cracks. Magnification of the fracture morphology 500 times revealed that under the action of freeze–thaw cycles, the transgranular failure area of the rock fracture surface increased gradually. This caused a shear failure trend in the macroscopic failure mode, which is consistent with the rock properties and the creep failure characteristics.

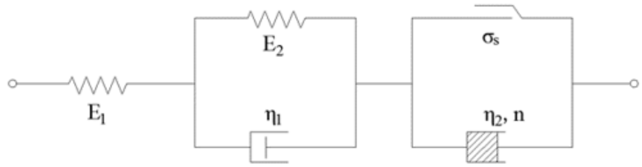

FIGURE 5. Rock viscoelastic–plastic creep model.

Comprehensive analysis of the mesoscopic damage phenomena in creep tests of freeze–thawed rock revealed that the damage inside the rock directly affects its long-term strength. Under the action of constant load, the internal rock particles are continuously deformed. This causes the coarse-grained corners or weak particles to incur more breakage and refinement, and the particle arrangement is further adjusted. However, the cohesive force between the particles limits its slippage so that the internal particles maintain a dynamic balance under the actions of external pressure and internal cohesion. In addition, the rock damage and deterioration caused by the freeze–thaw cycles caused an increase in porosity, and a decrease in the cohesive force between the particles. This results in macroscopic failure under the lower graded load, which reduces the long-term strength.

IV. CREEP MODEL ANALYSIS AND VERIFICATION OF FREEZE–THAW SANDSTONE

A. SELECTION OF CREEP THEORY MODEL

The creep characteristics of rocks are highly complex and often simultaneously include elasticity, plasticity, and viscosity [31], [32]. According to the creep test results of freeze-thaw rocks, the long-term strength of the rock decreased with the increase of the number of freeze-thaw cycles, and the rock total strain increased continuously. It showed that the rock exhibited the characteristics of elasticity, viscosity, viscoelasticity. Therefore, the authors adopted a nonlinear viscoelastic–plastic model considering the influence of freeze–thaw. The creep model consists of a series of elastic elements, Kelvin bodies, and nonlinear rheological elements [33], as shown in Fig. 5.

According to the constitutive model shown in Fig. 5, the corresponding state equation is

$$\left.\begin{aligned} &\sigma_1 = E_1\varepsilon_1 \\ &\sigma_2 = E_2\varepsilon_2 + \eta_1\varepsilon_2^g \\ &\sigma_3 = \sigma_S + \eta_2\varepsilon_3^g/(nt^{n-1}) \\ &\sigma = \sigma_1 = \sigma_2 = \sigma_3 \\ &\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \end{aligned}\right\}, \tag{1}$$

where ε is the total creep strain, E_1 and E_2 are the elastic parameters, η_1 and η_2 are the viscous coefficients, and n is the HVPB component parameter.

When $\sigma \leq \sigma_s$, where σ_s is long-term strength or yield strength, the model degenerates into a generalized Kelvin model with the following creep equation:

$$\varepsilon=\frac{\sigma_0}{E_1}+\frac{\sigma_0}{E_2}(1-e^{-\frac{E_2}{\eta_1}t}). \tag{2}$$

When $\sigma \geq \sigma_s$, its creep equation is

$$\varepsilon=\frac{\sigma_0}{E_1}+\frac{\sigma_0}{E_2}(1-e^{-\frac{E_2}{\eta_1}t})+\frac{(\sigma_0-\sigma_s)}{\eta_2}t^n. \tag{3}$$

The graded loading method was chosen because of the rock creep test. Therefore, the rock graded creep equation can be corrected to the following:

When $\sigma \leq \sigma_s$,

$$\varepsilon=\frac{\sigma_i}{E_1}+\frac{\sigma_i}{E_2}(1-e^{-\frac{E_2}{\eta_1}t})+\varepsilon'. \tag{4}$$

When $\sigma \geq \sigma_s$,

$$\varepsilon=\frac{\sigma_i}{E_1}+\frac{\sigma_i}{E_2}(1-e^{-\frac{E_2}{\eta_1}t})+\frac{(\sigma_i-\sigma_s)}{\eta_2}t^n+\varepsilon', \tag{5}$$

where ε' is the total strain of the rock at the beginning of the stage loading:

$$\varepsilon'=\sum_{j=1}^{i-1}\frac{\sigma_j}{E_2}(e^{\frac{E_2}{\eta_1}(t-t_{j+1})}-e^{-\frac{E_2}{\eta_1}(t-t_j)})(i=1,2,3\ldots), \tag{6}$$

where $\eta(n,t)=\frac{1}{\eta_2}t^{n-1}$.

B. PARAMETER IDENTIFICATION AND CORRECTION OF CREEP MODEL OF ROCK UNDER THE CONDITION OF FREEZE–THAW CYCLES

According to the experimental data, the rock creep model parameters were identified by (4), (5), and (6). In addition, the parameters of E_1, E_2, and η_2 under the conditions of the freeze–thaw cycles were obtained, as shown in Fig. 6.

The figure shows that as the graded load increased step by step, the elastic modulus E_1 of the first part of the freeze–thaw rock creep model increased and the elastic deformation under the same load decreased continuously, showing an exponential change. However the elastic modulus E_2 and the viscosity coefficient η_2 of the second part showed significant downward trends, and the maximum decrease in the viscosity coefficient reached 60%. Under a constant load, the elastic viscous deformation gradually increased until macroscopic damage occurred, which is consistent with the experimental data in Table 2. Under the same loading series, the creep modulus of different freeze–thaw cycles was basically the same. This indicates that the number of freeze–thaw cycles has little effect on the elastic deformation of the rock creep section, and the relationship between the elastic moduli E_1 and E_2 are shown in (7) and (8). At the same time, the viscosity coefficient η_1 under the same number of freeze–thaw cycles is nonlinearly fitted. The relationship between the

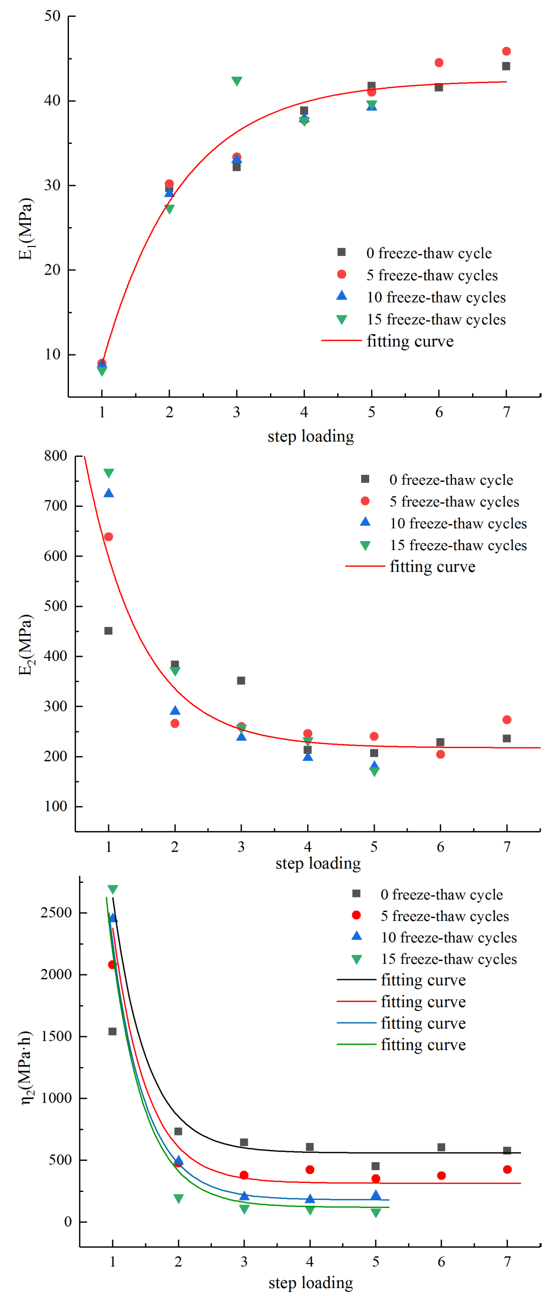

FIGURE 6. Parameter identification of creep model of freeze–thaw rock.

constants of different curves was obtained as shown by relationship between the viscosity coefficient and the graded loading series shown in Fig. 6(c). The viscosity coefficient with different loading stages and freeze–thaw cycles is shown in (9).

$$E_1 = 42.46-78.57e^{-0.85i} \tag{7}$$

$$E_2 = 220.93+2033.5e^{-1.43i} \tag{8}$$

$$\eta_1 = 69.96+13786.25e^{-2.31i}+489.53e^{-0.12b}, \tag{9}$$

where i is the graded loading series, and b is the number of freeze–thaw cycles.

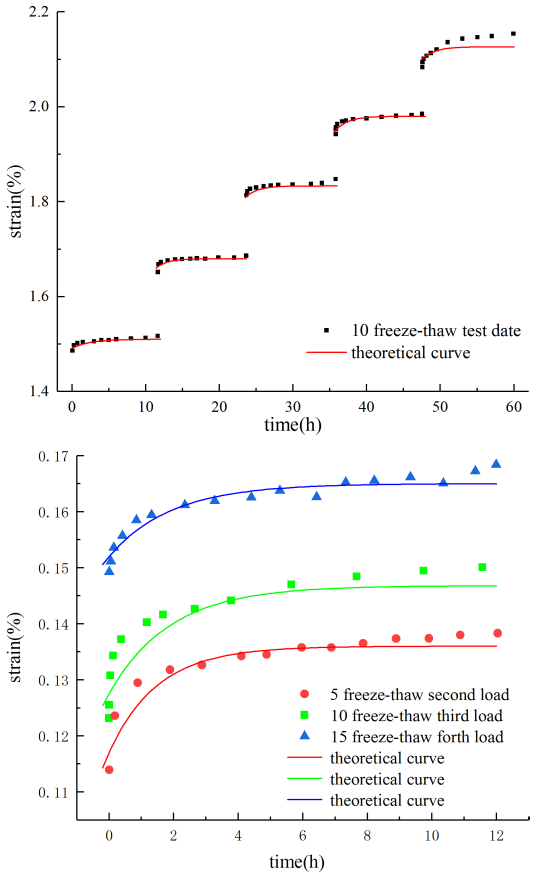

FIGURE 7. **Comparison of test data and theoretical curve.**

C. VERIFICATION AND DISCUSSION OF CREEP MODEL OF FREEZE–THAW ROCK

The freeze–thaw rock hierarchical loading data, shown in Fig. 7, were used to verify the hierarchical loading creep relationship of (4), (5), and (6) combined with the relationship of the elastic and viscous parameters in (7), (8), and (9).

As shown in Fig. 7, the theoretical curve of the creep model of the frozen–thawed rock was deviated from some of the experimental data, and the strain deviation value was less than 0.005%, which is within the allowable range of the error. This is attributed to the measurement error of the rock rheology tester and the strain data recording time interval during the creep test, which caused a certain degree of error in the test data. In the early stage of uniaxial compression creep section loading, the rock strain growth produced large error in the experimental data. When the loading entered the stable creep stage, the strain was basically unchanged. At that time, the theoretical model agreed well with the experimental data. At present, a large number of experimental studies have shown that the degree of damage caused by freezing and thawing is uncertain [34], [35]. It is difficult to accurately describe the relationship between the number of freeze–thaw cycles and rock damage. Moreover, allowable deviation exists between the theoretical model and the experimental data. In summary, the creep model established in this paper can describe the creep properties under different freeze–thaw cycles and graded loading stages. This model can be used to analyze the creep mechanical properties of rocks under freezing and thawing conditions.

V. CONCLUSIONS

In summary, this study investigated the effects of freeze–thaw and step loading and found that these factors had a significant influence on the creep of sandstone rock specimens. Prior to freeze–thaw cycle exposure, the creep characteristics of rock specimens were observed. The following conclusions can be made:

1) With the increase in the rock loading load, the elastic deformation decreases and the viscoplastic deformation increases; as the number of freeze–thaw cycles increases, the maximum loading stress of rock continues to decrease, and its long-term strength deteriorates.

2) Under the action of freezing and thawing, the porosity of the sandstone continues to increase, the cohesive force between the particles inside the rock decreases continuously, and the pore structure continues to deteriorate, forming a dense network of fractures, which results in conjugate shear failure of the rock under low-level graded load.

3) The nonlinear creep constitutive model of frozen–thawed sandstone was established and the parameters were identified. The creep constitutive equations considering the number of freeze–thaw cycles and graded loads were obtained, and the experimental data were used to verify the creep model. It shows that the established creep model can accurately reflect the graded loading creep state of frozen–thawed sandstone.

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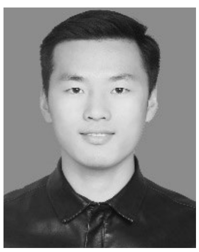

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