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Shear relaxation characteristics of rock joints under stepwise loadings

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ABSTRACT

The stress relaxation characteristic of rock mass is an important aspect of rheology and has important practical significance for rock engineering. In order to investigate the relaxation characteristic of rock joints with different slope ratios and normal stresses, a series of shear stress relaxation tests were conducted on artifical rock joints poured by cement mortar. Test results show that the relaxation curves can be divided into three stages, i.e. instantaneous relaxation stage, attenuation relaxation stage, and stable relaxation stage. Furthermore, the nonlinear Maxwell relaxation equation was obtained by using the relation between the viscosity coefficient and time, and the theoretical curves based on the empirical equation agreed well with the test results. Moreover, the change law of the initial viscosity coefficient was investigated. Accordingly, a stress relaxation method, termed as relaxation stress peak method, was proposed to determine the long-term strength of rock joints.

1. Introduction

Rock mass is a type of complex and heterogeneous geologic body that comprises various structural planes. In practical applications, the mechanical properties of structural planes usually control the stability of the rock engineering. Numerous studies have been carried out to investigate the mechanical behaviors of structural planes of rock mass [1–9]. The influences of roughness, stress level and stress rate on the failure mechanism of structural planes have been analyzed, and valuable findings have been obtained. Some experimental results and methods provide important references for current experimental studies and engineering practices.

Rheology is one of the most important mechanical properties of rock mass. Creep and stress relaxation are two main parts of the rheological property. Currently, the studies on the rheological properties of rock mass mainly focus on their creep behavior; abundant results have been obtained as regards both theoretical and practical aspects [10–15]. However, stress relaxation failure is a common phenomenon in practical rock engineering, especially surrounding rock in underground opening engineering [16]. Although researchers have realized the importance of the relaxation properties of rock mass,

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relevant studies are still few, because the deformation of sample needs to remain constant during the stress relaxation test, which was hardly implemented with early general testing machines [17]. The early studies on stress relaxation of rock mainly focus on salt rock and rock burst [18,19]. Afterwards, some stress relaxation tests were carried out with other types of rock under uniaxial and triaxial conditions, and the constitutive models were investigated [20–22]. Yahya [23] mentioned that stress relaxation can be considered as the transformation from elastic deformation to non-elastic deformation, and he proposed a unified constitutive model to describe the creep and relaxation behavior of salt rock. Xiong [24] carried out stress relaxation tests of green schist samples under uniaxial and biaxial conditions, and he found that the relaxation curves of axial stress and lateral stress displayed a stepwise decreasing trend. Liu [25] adopted the cyclic loading method to carry out relaxation tests on Barton's curve structural planes' casting by cement mortar, and observed three stages in the relaxation process. However, due to the complexity of the mechanical properties of natural structural planes, it is rather difficult to consider various parameters of the structural plane, such as roughness, stiffness, and shear strength. Currently, there are few findings about the relaxation properties of structural planes, and further studies are still necessary.

Rock mass engineering usually failed after a long period of rheological deformation. Generally speaking, it is the long-term strength related with the time factor, rather than instantaneous strength, which controls rock mass stability. Long-term strength could be regarded as the ultimate strength in which the influence of time factor has been considered. At present, there are mainly direct and indirect methods to determine long-term strength. The direct method consists in carrying out creep tests on rocks under loadings of different stress levels till failure, and calculates the long-term strength according to the relationship between stress level and failure time. Though the direct method is theoretically reliable, it is time-consuming and requires many samples, which is likely to cause big errors because of the heterogeneity of different samples. Therefore, the direct method is seldom adopted [26]. The indirect method consists in seeking a critical value or criteria of the strength under the function of different external forces in different development stages through observing the physical and mechanical phenomena of rocks occurring while creep tests are under way. It usually calculates the long-term strength according to the results of creep failure tests with step loading. Commonly adopted indirect methods include the transition creep method [10] and the isochronous stress–strain curve method [27], etc. With the improvement of the experimental techniques, methods for determining the long-term strength, such as the crack damage stress method, the volume strain method as well as the axial and lateral creep rate intersection method, have been proposed based on triaxial loading and unloading rheological tests on rocks [28–30]. All these methods that were used to determine long-term strength are based on the results of rock creep tests. Creep deformation and relaxation are equivalent in essence in terms of the flowing deformation properties of rocks, which are two idealized mechanical concepts of the long-term mechanical properties of rock materials [10]; therefore, the long-term strength of rocks can also be obtained through stress relaxation tests. Liu [25], Pushkarev [31] put forward their respective methods to determine long-term strength based on relaxation tests under conditions of cyclic loading, the essence of which is regarding the stress that could not cause additional viscous deformation as the long-term strength. Due to the limitation of the testing methods, researches on rock stress relaxation and long-term strength are relatively insufficient. Carrying out researches on the relaxation properties of structural planes of rock mass and predicting long-term strength based on relaxation tests can allow us to comprehensively understand the effective mechanical properties of rocks and provide a reliable theoretical basis for evaluating the long-term stability of rock mass engineering. Therefore, it is significantly valuable in the field of theoretical research and engineering.

In this work, a series of tests on the shearing mechanical properties of a sample of structural planes under relaxation conditions has been carried out. Based on the analysis of experimental results, it elaborates the relaxation laws of structural planes, analyzes the influence of normal stress and of the angular dimensions of structural planes on the relaxation rate and the reduction value of stress during the tests; it adopts the parameter nonlinear Maxwell relaxation model to describe the test curves; it puts forward methods for determining the long-term strength and relevant theory through stress relaxation tests based on the method allowing one to determine the long-term strength through creep tests. It analyzes the relationship between relaxation rate and stress level and testifies to the feasibility of determining long-term strength with the method proposed in the paper from another perspective.

2. Materials and methods

2.1. Test equipment

The tests are completed on Changchun CSS-1950 rock biaxial creep testing machine in Tongji University (as shown in Fig. 1), using the built-in software system to control the test process with servo motor and automatically collect test data and set acquisition accuracy according to the test's requirements. The testing machine can exert vertical axial loading and horizontal axial loading simultaneously or respectively, with a maximum vertical axial pressure of 500 kN and a maximum horizontal axial pressure of 300 kN. It can simultaneously measure the biaxial and bilateral deformation values of samples. The deformation measurement range is ± 3 mm and the deformation measurement precision is 0.001 mm, which can satisfy the accuracy requirement of the tests.

2.2. Materials preparation

Due to the complexity of the forms of natural structural planes and the huge difference in the nature of their fillings, there is high discreteness in test results, which in turn increases the difficulty of analysis. Therefore, in order to reduce

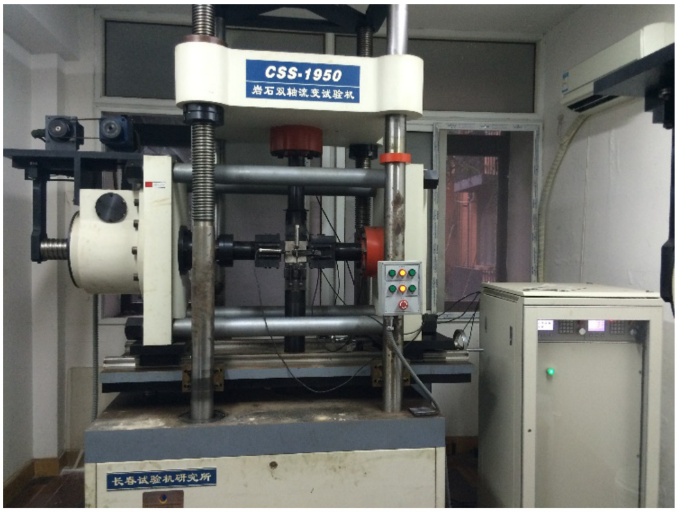
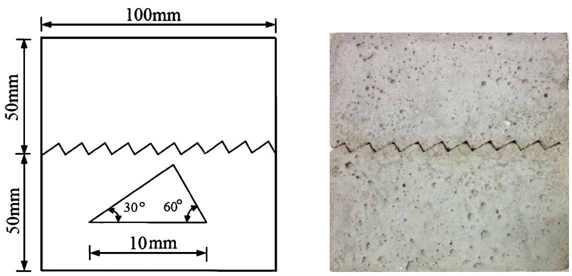


Fig. 1. Experimental equipment.



(a) Section size (b) Sample

Fig. 2. Ichnography of the dentate discontinuities.

the complexity of structural planes and maintain their relative homogeneity, the test makes use of cement mortar samples with regular dentiform structural planes and carries out fundamental test researches on the relaxation properties of the structural planes. In order to avoid differences in test results caused by different sample materials, the samples adopt the same material, mixed proportion, maintenance time, and mold. The specifications of the samples are: 10 cm $\times$ 10 cm $\times$ 10 cm; the length of a single dent of regular dentiform structural planes is 10 mm, 10 dents in total, which adopt three different ascending angles, namely 10°, 30° and 45° (as shown in Fig. 2). The model materials include 32.5R cement, standard sand and water, whose proportion in the mixture is water:cement:sand = 1:2:4. The materials are evenly mixed according to the proportion, tamped in steel molds and smoothed down, so as to reduce unfavorable impact during sample preparation. The mold is removed 24 h after the models have been shaped; and 28 days are needed for maintenance.

2.3. Test methods and loading methods

Before the relaxation tests, the uniaxial compression and shear tests of the complete cube samples were carried out. According to the testing results, the mean values of uniaxial compressive strength is 19.62 MPa, the cohesive force is 4.19 MPa, and the friction angle is 43°. The relaxation test adopts the method of step loading, the normal stresses during the tests are 10%, 20%, 30% of the uniaxial compressive strength of the complete cube samples, respectively. The shear strength is loaded step by step according to 40%, 60%, 80%, 90% and 95% of $\tau_{\max}$ of the structural planes with different ascending angles under the same normal stress. The loading steps in the relaxation tests are shown in Fig. 3. The loading steps include: (1) the normal stress is applied firstly to an index value (1.962 MPa, 3.924 MPa, and 5.886 MPa) with a rate of 0.2 kN/s. Normal stress is constant during the test and then the shear stress is exerted when the normal deformation becomes stable; (2) when the normal deformation is stable, an initial shear stress τ_0 is exerted till 40% of the shear strength $\tau_{\max}$ (i.e. Section OA), the loading rate of which is 0.2 kN/s. Thereafter, shear stress relaxation test is conducted for 72 h, during which the corresponding strain after loading, ε_A, is kept as a constant. With the stress decreases, the stress–strain curve moves from point A to point B; (3) starting from point B, an initial shear stress τ_0 is exerted at the rate of 0.2 kN/s till 60% of shear strength $\tau_{\max}$ (i.e. Section BC), then step (2) is repeated till the end of the test. During the tests, the testing

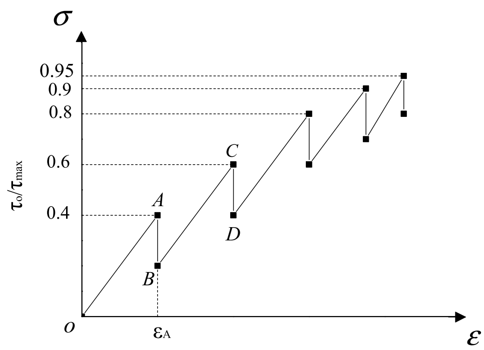


Fig. 3. Diagram of the stress–strain curve during the relaxation test.

machine automatically collects the stress values. Each sample is exerted with 5 levels of shear strength and last for 360 h in total, and the indoor temperature remains constant.

3. Test data and analysis of the results

3.1. Relaxation properties of the structural plane

Under different normal stresses, the relaxation curves of the structural planes with ascending angles of 10°, 30° and 45° are shown in Fig. 4. From Fig. 4, one can see that the stress relaxation tests of the structural planes possess the following characteristics: (1) the relaxation curves of structural planes under different normal stresses and with different ascending angles are similar in shape; after loading is completed, the stress significantly decreases as time goes by in constant strain conditions, which conforms to the general relaxation rules of materials. (2) The relaxation curves are mostly characterized by continuous stress relaxation, yet the stress tends to be stable, instead of being zero; therefore, the curve is not a complete stress decay curve; (3) at the beginning of each relaxation step, the initial shear stresses are at the same level; therefore, under the same normal stress, the initial shear stress increases with increasing the ascending angle, which leads to the stepped change of the curve with the increase of the ascending angle during the whole relaxation process.

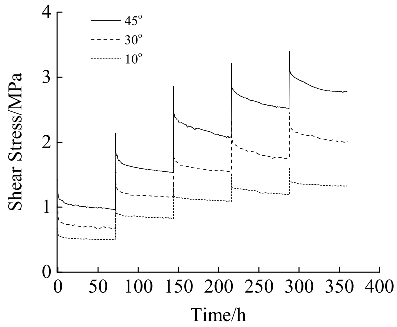
3.2. Relaxation rate analysis

Through calculating the slope of the relaxation curve at different times, the changing curve of the relaxation rate with time is obtained. To avoid the influence of the loading history on stress relaxation, the relaxation rate curve adopts data under Grade-1 stress level (i.e. $\tau_0 = 0.4\,\tau_{\max}$) for analysis. When the normal stresses are 1.962 MPa and 5.886 MPa, the relaxation rate curves of the structural planes with the ascending angles of 10° and 45° under Grade-1 stress level are as shown in Figs. 5 and 6. Since the rate changes rapidly at the beginning of relaxation and does not last long, semi-logarithm coordinates are adopted in the image to better analyze the relaxation rate curves.

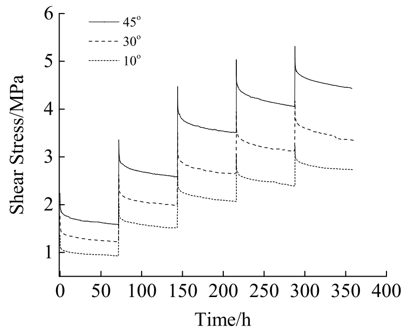
According to the change of the speed of relaxation rate, the relaxation rate curves of structural planes under different normal stresses and with different ascending angles in Fig. 5 and Fig. 6 can be classified into two stages: (1) attenuating relaxation stage – the relaxation rate in this period decreases at a very fast speed with the increase of time; (2) steady relaxation stage. After the attenuating relaxation stage, with the increase of time, the relaxation rate value basically remains unchanged and the corresponding relaxation rate is a steady relaxation rate. When the ascending angle of the structural plane remains unchanged, the larger the normal stress is, the greater the initial relaxation rate is. For instance, when the ascending angle of the structural planes is 10°, the initial relaxation rates are 0.876 MPa/h and 2.41 MPa/h respectively under the normal stresses of 1.962 MPa and 5.886 MPa. Under the same normal stress, the larger the ascending angle is, the larger the initial relaxation rate is. For example, when the normal stress is 5.886 MPa, the initial relaxation rates are respectively 2.41 MPa/h and 3.912 MPa/h when the ascending angles of the structural planes are 10° and 45°. Yahya [23] regards the relaxation process as the transformation process from elastic deformation to plastic deformation. It can be considered that the speed of initial relaxation rate is related to the release rate of elastic deformation energy. During the loading process, the larger the normal stress and the ascending angle are, the more elastic the deformation energy is; when the relaxation is carried out under constant strain, the faster the energy release is, the larger the relaxation rate is.

3.3. Relaxation stress

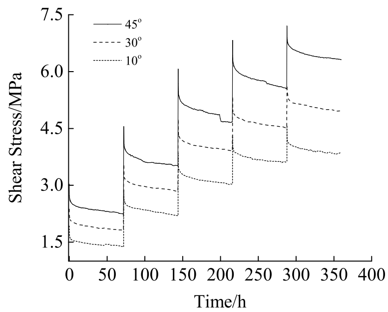
In order to further analyze the stress relaxation properties of structural planes with different ascending angles, the relaxation stress of the structural plane at time t is defined as $\Delta\tau = \tau_0 - \tau_f$. τ_0 is the initial shear stress at the beginning of each step, $\tau_f(t)$ refers to the surplus shear stress after t hours of relaxation, and $\Delta\tau$ refers to the difference between the initial shear stress and the surplus shear stress. Since the shear strengths of structural planes are different, the exerted



(a) $\sigma = 1.962$ MPa



(b) $\sigma = 3.924$ MPa

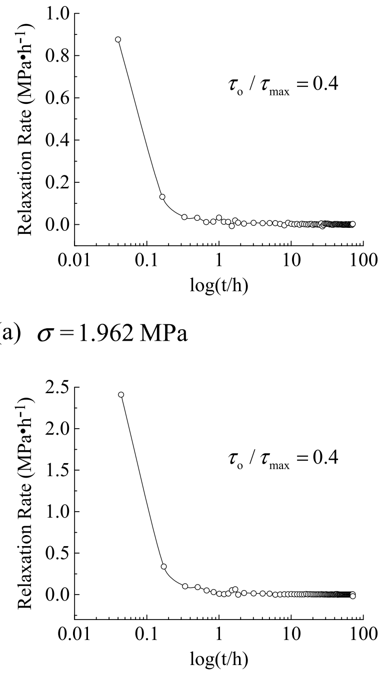


(c) $\sigma = 5.886$ MPa

Fig. 4. Stress relaxation curves under different normal stresses.

initial shear stresses shall be different accordingly. For the convenience of the comparative analysis, the changing curves of the relaxation stress of the structural plane with time under different ascending angles and different normal stresses are drawn as shown in Fig. 7 under the same stress level (i.e. $\tau_0/\tau_{\max}$, the ratio of the initial stress to the shear strength).

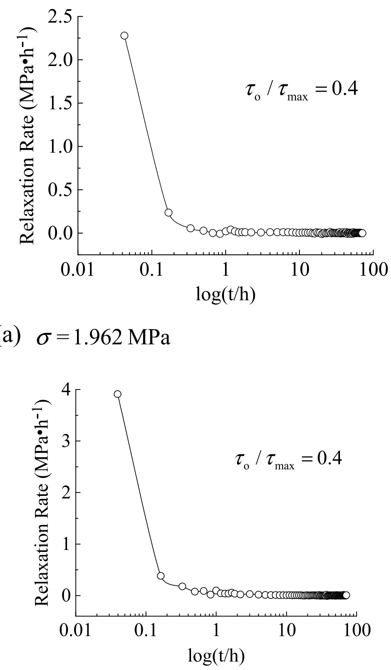
As shown in Fig. 7a, the changing curve of time and $\Delta\tau$, the relaxation stress of the structural planes with different ascending angles under the same stress level when $\sigma = 3.926$ MPa, the relaxation stress $\Delta\tau$ increases with increasing the ascending angle; the larger the ascending angle is, the greater the instantaneous relaxation amount is, the longer the attenuating relaxation lasts, and the greater the rate in achieving steady relaxation. For example, when the relaxation time is within 30–72 h, the steady relaxation rate is 1.0×10^{-3} MPa/h when the ascending angle is 10°, and the steady relaxation rate is 1.9×10^{-3} MPa/h when the ascending angle is 45°. Fig. 7b shows the changing curve of time and $\Delta\tau$, the relaxation stress of the structural planes with the ascending angle of 45° under different normal stresses, which demonstrates similar rules as in Fig. 7a. From the image, the relaxation stress $\Delta\tau$ constantly increases with increasing the normal stress; the larger the normal stress is, the greater the instantaneous relaxation amount is, the longer attenuating relaxation lasts, and the greater rate in achieving steady relaxation is. Therefore, the relaxation speed in the steady relaxation stage is not 0, yet the rate is a constant that close to 0. Liu [10] points out that rocks will display creep deformation under the function of external loading; loading relaxation will happen when the strain of samples remain constant, till the acting force and the internal stress have reached balance; the loading is known as a “stable stress”. From the perspective of energy, under a same shear stress, relatively larger normal stress and ascending angle, which facilitates energy accumulated during the



(a) $\sigma = 1.962$ MPa

(b) σ=5.886MPa

Fig. 5. Relaxation rate curve of structural planes with an ascending angle of 10°.



(a) $\sigma = 1.962$ MPa

(b) $\sigma = 5.886$ MPa

Fig. 6. Relaxation rate curve of structural planes with the ascending angle of 45°.

loading process, would cause a relatively greater relaxation stress within the same time, and the longer time is needed for achieving a "stable stress", a state of balance between external and internal stresses.

The power-law function is usually adopted to describe the relationship among stress, strain and time of nonlinear viscoelastic materials [32]. Therefore, it can also be adopted to describe relaxation stress curves, i.e. Eq. (1):

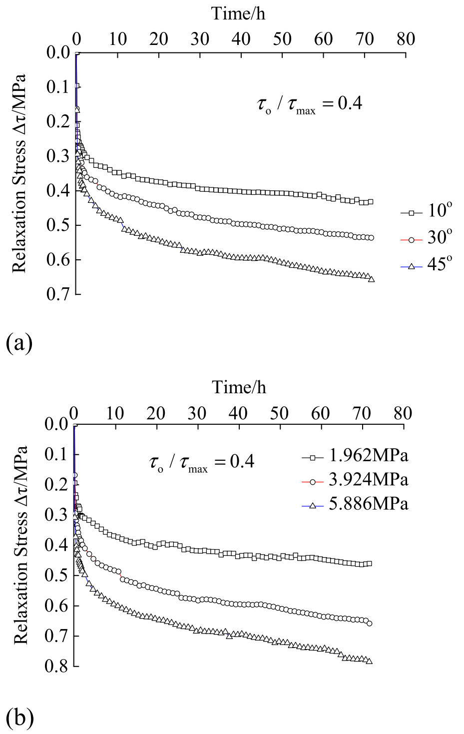


Fig. 7. Relationship between $\Delta\tau$ and time: (a) relaxation stress curves of the structural planes with different ascending angles when $\sigma = 3.962$ MPa; (b) relaxation stress curves under different normal stresses when the ascending angle is 45°.

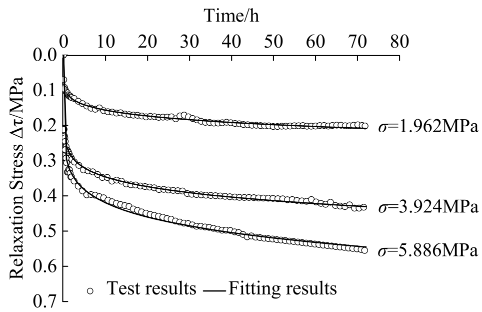


Fig. 8. Comparisons between tests results and fitting results when the ascending angle is 45°.

$$\Delta \tau (t) = kt'' \qquad (1)$$

where t refers to time, p and n are two material constants. Fitting calculations is carried out with Eq. (1) on the structural plane with an ascending angle of 10° under different normal stress, and the results are drawn in Fig. 8. It is can be observed from the image that there is good fitting correlation between the fitting results and the test curves; the correlation coefficients are above 0.95; the proposed formula can reflect the changing process of relaxation stress $\Delta\tau$ with time.

From the above analysis, it can be inferred that the relaxation process of structural planes is related to the ascending angle and the normal stress, which have different degrees of influence on the two stages of the relaxation process, the whole tendency is that the stress constantly decreases and becomes stable, yet the stress is not completely attenuated. Since rock is a complex heterogeneous body, when the relaxation is carried out on the samples with constant stain level under different initial shear stresses, the internal structure and the deformation of samples change (internal microcracks of rocks extend and expand, which lead to the transformation from elastic deformation to viscoplastic deformation during loading), and stress is adjusted and transferred (cracks and viscoplastic deformation can reduce stress concentration within the rock medium, the internal stress constantly decreases and generate relaxation). Therefore, the stress relaxation process is the process of constant adjustment and transfer of the internal stress of rocks till the internal stress and external acting force achieve balance.

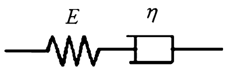


Fig. 9. Maxwell model.

4. Stress relaxation equations and parameter fitting analysis

Component combination models in rheological mechanics are widely adopted in engineering for the simple and intuitive structure and definite physical meanings of parameters. However, most models ignore the nonlinearity of parameters, i.e. correlation with time. In practice, the parameters of models display nonlinear variation under different stress levels, different stress strain states and the stress effect duration. As a result, the time effect of rock mechanics parameters shall be considered so as to accurately describe rock relaxation properties.

Maxwell's model is connected with an elastic component and a viscous component, as shown in Fig. 9.

The relaxation equation of the model is:

$$\tau(t) = \tau_0 \mathrm{e}^{-\frac{\eta}{G}t} \tag{2}$$

where τ_0 refers to the initial stress. Equation (2) shows that, when ε remains unchanged, the stress τ will decrease with increasing time and tend to be zero, which is not consistent with the stable value of the stress curve as shown in Fig. 4. Liu [10] assumes the viscosity coefficient η to be a function of the loading stress and the time in creep test analysis. In our relaxation test, the stress is loaded to a certain value and then stop exerting an acting force on the samples, which is different from the creep test. So, the influence of stress on the viscosity coefficient η is not considered. It is only assumed that the viscosity coefficient η is a function of time t and conforms to the line function relationship, i.e.:

$$\eta(t) = A + Bt \tag{3}$$

In the equation above, A and B are constants. A refers to the initial viscosity value of the samples at the time of loading ($t = 0$); B stands for the change rate of the viscosity coefficient. According to the series rules of component combination models, the constitutive equation is obtained:

$$\dot{\varepsilon} = \frac{\tau}{A + Bt} + \frac{\dot{\tau}}{G} \tag{4}$$

During the relaxation, since the strain is hold as a constant, Eq. (4) could be written as:

$$0 = \frac{\tau}{A + Bt} + \frac{\dot{\tau}}{G} \tag{5}$$

The solution to the above equation can be obtained:

$$\tau(t) = C \times \mathrm{e}^{-\frac{G}{B}\ln(A+Bt)} \tag{6}$$

where C is an undetermined coefficients. Substituting the initial condition of relaxation, i.e. $t = 0$, $\tau = \tau_0$, into Eq. (6), C can be determined as:

$$C = \tau_0 \mathrm{e}^{\frac{G \ln A}{B}} \tag{7}$$

Substituting Eq. (7) into Eq. (6), the relaxation equation of nonlinear Maxwell model can be obtained as:

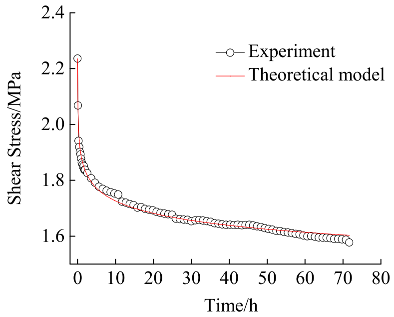
$$\tau(t) = \tau_0 \mathrm{e}^{\frac{G}{B}\ln(\frac{A}{A+Bt})} \tag{8}$$

In the equation, τ_0 refers to the initial shear stress at the beginning of relaxation; G is the shear modulus; A and B are parameters obtained from the fitting.

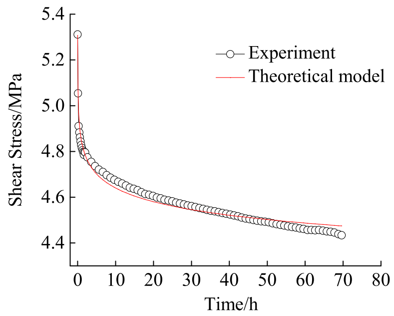
According to Eq. (8), the fitting is made with the stress relaxation curve of the structural plane with the ascending angle of 45° under the normal stress of 3.962 MPa, as an example, with the aid of Matlab numerical calculation software and the least square method. The fitting results are as shown in Fig. 10, the numbers in the image stand for shear stress levels, i.e. the ratio of initial shear stress τ_0 and shear strength $\tau_{\max}$. Please refer to Table 1 for the fitting parameters.

It can be inferred from Fig. 10 and Table 1 that when adopting the relaxation equation proposed in the paper to make fitting on the stress relaxation curve of the structural plane with the ascending angle of 45°, the relevant parameters are high, which means a good agreement between the curves. Besides, the shape and tendency of the test curve and fitting curve are basically the same, which means that the nonlinear Maxwell model relaxation equation can reflect the shear stress relaxation properties of the structural planes.

In this work, the parameter A is relatively stable, and the parameter B changes with increasing stress and ascending angles. For a given structural plane, the essential contributions to its relaxation behavior are the frictional resistance and internal kinematic constrains between the contacted surfaces. The magnitude of these contributions depends on the normal



(a)



(b)

Fig. 10. Fitted curves of structural planes with the ascending angle is 45°. (a) $\sigma = 3.924$ MPa, $\tau_0/\tau_{max} = 0.4$; (b) $\sigma = 3.924$ MPa, $\tau_0/\tau_{max} = 0.95$.

Table 1
Parameter values of the structural planes with an ascending angle of 45° when $\sigma = 5.886$ MPa.

Shear stress	τ_0/τ_{max}	τ_0 (MPa)	G (GPa)	A (GPa·h)	B (GPa)	R
1	0.4	2.235	0.502	0.138	13.38	0.990
2	0.6	3.352	0.561	0.283	18.97	0.990
3	0.8	4.469	0.630	0.252	23.28	0.993
4	0.9	5.028	0.604	0.304	25.85	0.980
5	0.95	5.307	0.576	0.236	30.76	0.979

stress and on the geometric features of surface asperities in structural plane (e.g., size, morphology, and roughness). Prior to the relaxation stage, because the asperities on the opposite surfaces of structural plane are brought together and interlocked by the normal stress, the increasing shear stress will accumulate on the contacted surface and provoke the internal kinematic behaviors associated with dilatancy and crushing/breakage between the contacted asperities. As a result, dilatancy in the normal direction will be suppressed by the applied normal stress and the morphology of asperities. For the relaxation test, since the shear stress is decreasing to a relatively lower value over time, the dilatancy will be fully suppressed. In case of the same normal stress, the difference of relaxation behaviors will be controlled by the magnitude of the shear stress and the morphology of the asperities (e.g., roughness). We adopt structural planes with different ascending angles in this work. A higher shear stress will cause a higher local stress. A lower ascending angle represents a lesser contact surface left after initial loading, and also causes a higher local stress in the contacted surface. A relatively higher local stress will bring a higher potential local failure. The magnitude of such local failure changes the relaxation rates resulting in the variation of parameter B.

5. Determination of the long-term strength of the structural plane

Creep deformation refers to the slow increase of deformation with time under the effect of constant stress, while relaxation refers to the gradual decrease of stress with time under the effect of a constant stress. Creep and relaxation are two intrinsic time-dependent behaviors of materials caused by different boundary conditions [33]. Because of different boundary conditions, rocks become relaxed with the constraint of strain, part of the loading transfers to other inside particles and causes creep deformation. The development of creep deformation further promotes the generation of relaxation. Besides, most of current relaxation theories are based on creep deformation theory; therefore, relaxation can be seen as another

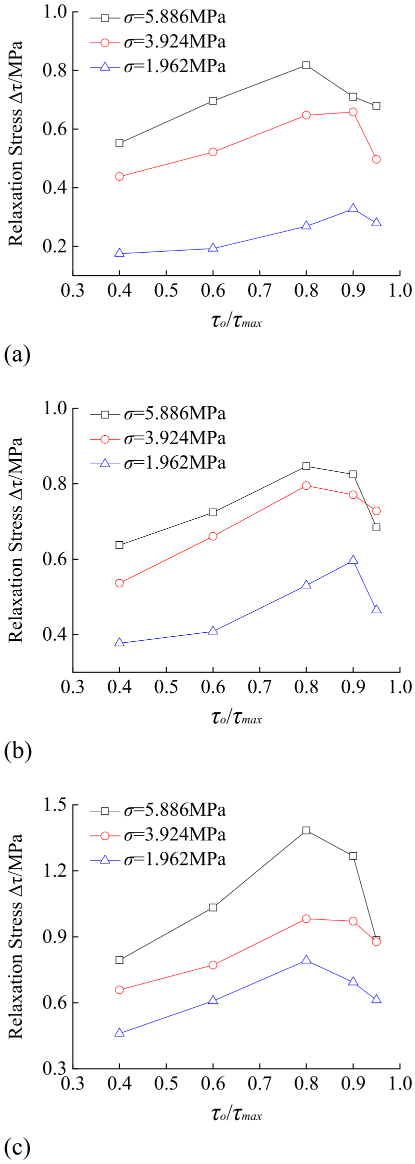


Fig. 11. Relationship between the maximum relaxation stress $\Delta\tau$ and the shear stress levels: (a) structural planes with an ascending angle of 10°; (b) structural planes with an ascending angle of 30°; (c) structural planes with an ascending angle of 45°.

manifestation of creep deformation to a certain degree. As a result, the paper probes into the method of determining the long-term strength of rocks through relaxation tests.

5.1. Relationship between relaxation stress and stress level

The changing curves of relaxation stress of structural planes with the ascending angles of 10°, 30°, and 45° under three different normal stresses in accordance with the changes of initial shear strength are displayed in Fig. 11. From the image, it can be seen that, under the same shear stress level, the greater the ascending angle and the normal stress are, the greater the relaxation stress of the structural plane is; regarding structural planes with the same ascending angle, the larger the normal stress is, the larger the relaxation stress is; and the larger the shear stress level is, the larger the relaxation stress is; however, the relaxation stress takes a peak value, rather than keeping increasing with increasing the stress level. When the normal stress is 1.962 MPa, the relaxation stress of structural planes with ascending angles of 10° and 30° reaches the peak when the shear stress level is $\tau_0/\tau_{\max} = 0.9$ and the relaxation stress of structural planes with the ascending angle of 45° reaches the peak when $\tau_0/\tau_{\max} = 0.8$; when the normal stress is 3.924 MPa, the relaxation stress of the structural planes with the ascending angle of 10° reaches the peak when $\tau_0/\tau_{\max} = 0.9$ and the relaxation stress of structural planes with ascending angles of 30° and 45° reaches the peak when $\tau_0/\tau_{\max} = 0.8$; when the normal stress is 5.886 MPa, the relaxation stress of all the structural planes, with ascending angles of 10°, 30° and 45°, reaches the peak when $\tau_0/\tau_{\max} = 0.8$, and then gradually decreases. When the normal stress and ascending angle are small, the relaxation stress reaches the peak when the stress level is 0.9; when the normal stress and the ascending angle are large, the relaxation stress reaches the peak when the stress level is 0.8.

5.2. Determining the long-term strength by relaxation tests

In the relaxation test, the strain remains constant and the stress gradually decreases. From the relationship equation $\sigma = E\varepsilon$ of elastic stress and strain, when the elastic modulus remains unchanged, the stress decreases, meaning the decrease of elastic deformation. The decreased elastic deformation is transformed into plastic deformation. The variation of the relaxation stress is dependent on the amount of transformation from elastic deformation into plastic deformation.

According to the mechanism of transition creep deformation method, there are only elastic and viscoelastic deformation when the stress is smaller than long-term strength; and there is unrecoverable plastic deformation when the stress is larger than the long-term strength. Therefore, the relaxation test can be interpreted in this way, when the initial shear strength τ_0 is smaller than long-term strength τ_∞, the stress is in direct proportion to elastic deformation, which means that the greater the stress is, the larger the elastic deformation will be, the amount of elastic deformation transformed into plastic deformation will increase accordingly, and the relaxation stress will be greater; when the initial shear strength τ_0 is larger than the long-term strength τ_∞, the deformation components change, which includes elastic deformation and plastic deformation. The generation of plastic deformation leads to the decrease of elastic deformation, the amount of elastic deformation transformed into plastic deformation decreases accordingly and the relaxation stress also decreases. The phenomenon that the relaxation stress reaches a peak value instead of keeping increasing with the improvement of the stress level is also explained in Fig. 10.

Based on the above analysis, the method of relaxation test with step loading is proposed to determine the long-term strength of rocks, i.e. the shear strength when the relaxation stress reaches its peak value shall be the long-term strength. Its mechanism of determining long-term strength can be consistent with transition creep deformation method. According to the method of determining long-term strength proposed in the paper, when the normal stress and the ascending angle of structural plane are quite small, the ratio of long-term strength τ_∞ and shear strength $\tau_{\max}$ is around 0.9; when the normal stress and the ascending angle of structural plane are quite large, the ratio of long-term strength τ_∞ and shear strength $\tau_{\max}$ is around 0.8. Under the function of small normal stress, the long-term strength of structural plane is mainly in the form of friction of structural plane; with the increase of the ascending angle, the friction strength turns into gear cutting strength, yet the difference between long-term strength and instantaneous strength of friction is quite small, and the difference between long-term strength and gear cutting strength is quite large. Under the function of large normal stress, the friction mechanism of the ascending angle basically disappears, and the long-term strength of the structural plane is mainly in the form of a gear cutting strength, in which the influence of the ascending angle is weakened. Therefore, for the sake of safety, the shear stress when $\tau_0/\tau_{\max} = 0.8$ can be adopted as the long-term strength of the structural plane. It is basically similar to the result in Xiong [24], who adopted the same loading method and carried out creep deformation tests on regular dentiform structural planes with ascending angles of 30° and 45°, and determined that the long-term strength is 80% of the shear strength with the aid of the isochronous curve method. Under general circumstances, the long-term strength can only be determined through a loading range, since it is difficult to directly obtain the corresponding shear strength of the relaxation stress with the step loading method. The more steps taken in the test, the difference between two adjacent loading values will be smaller, the range of the long-term strength will be smaller, and the value will be more accurate.

5.3. Discussion on the long-term strength determinations using creep and relaxation tests

The long-term strength is the maximum load that rocks can endure to maintain long-term stability; it is usually determined through indirect methods of creep test. The transition creep method is a direct and simple one among various methods.

Liu [10] points out that the maximum loading value when the steady-state creep rate is zero shall be the long-term strength of rocks. In other words, the maximum loading value when the attenuation creep occurs shall be the long-term strength of rocks. According to the typical creep curve characteristics, unloading in the steady-state creep stage causes deformation that instantaneously recovers and recovers with time, as well as partial deformation, which remains in the materials and becomes permanent deformation; in contrast, unloading in the attenuation creep stage causes elastic deformation of materials that can partially instantaneously recover and partially recover with time. Therefore, the transition creep method can be interpreted as the maximum load that corresponds to the generation of viscoelastic strain or the maximum stress that does not generate unrecoverable plastic deformation.

According to the long-term strength determination using the transition creep method, when the stress is smaller than long-term strength, rocks are in the elastic stage; when the stress is larger than the long-term strength, rocks are in the plastic stage. From the perspective of energy, when rocks are in the elastic stage, the behavior of energy is mainly embodied in energy accumulation; when the elasticity modulus remains constant, the higher the stress level is, the more energy will be accumulated. Since there is no input of energy during the relaxation process, when the deformation is under constant constraint, the stress would be released in a relatively rapid speed resulting from the more accumulated energy during loading process, which therefore generates a relatively large relaxation stress. When the stress is larger than the long-term strength, since the generation of plastic deformation will consume a large amount of energy, the accumulated energy will decrease, so the relaxation stress will also decrease. Through the above analysis, the validity of the long-term strength determination proposed in this study, which could be well consistent with the long-term strength determination using transition creep method, is further verified from the perspective of energy.

6. Conclusions

Through the shear relaxation test of regular dentiform structural planes and analysis of the results of the test, the following conclusions are reached.

1) The shear relaxation rules of a regular dentiform structural plane conform to the practical stress relaxation properties of general materials. The relaxation effect is obvious; the relaxation curve is an attenuation curve, involving two stages, attenuation relaxation and steady relaxation, with no relaxation failure stage.

2) According to the nonlinearity of the rheological parameter, the relaxation equation of the nonlinear Maxwell model is proposed to fit the relaxation curve of the structural plane with an ascending angle of 45°. There is high-degree agreement between the fitting curve and the test curve, which can basically describe the shear relaxation process.

3) The curve of the relaxation stress and the loading stress level of the regular dentiform structural plane shows that under the same shear stress level, the larger the ascending angle and the normal stress are, the greater the relaxation stress of the structural plane is; for the structural planes with the same ascending angle, the larger the normal stress is, the larger the relaxation stress is; and the higher the shear stress level is, the larger the relaxation stress is, yet the relaxation stress takes a peak value, instead of keeping increasing with increasing the normal stress.

4) On the basis of discussing the relaxation properties of the samples, the method of determining the long-term strength through the step loading relaxation test is proposed, i.e. the corresponding shear strength of the stress peak value of relaxation is the long-term strength of rocks.

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