Rheological test of soft hard interbedded rock mass

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Abstract. The effect of stress level and loading path on rheological behavior of alternating distribution of soft and hard rock layers are investigated with triaxial creep and uniaxial experiments. The results have shown that different stress states and loading paths have some influence on the rheological behavior of the rock mass. The creep displacement of the rock mass is increased and the lower the confining pressure is, the more obvious the rheological property of the rock mass is, which indicates that the confining pressure has a certain inhibitory effect on the rheology of rock mass.

1. Introduction
The rheology of rock generally refers to the phenomenon that the stress and strain of rock change slowly with time under the action of relatively stable load. In recent years, many important achievements have been made at home and abroad in research of rock rheological properties. At present, most of the researches on the rheological behavior of rock are for soft rocks or some rocks with single lithologic structure. A large number of on-site surveys and laboratory tests show that rocks with different lithology and structural surfaces also have different rheological properties. Some hard rocks, such as limestone and sandstone, can keep their steady creep stage for a long time, while some soft rocks like mudstone, shale and salt rock possess very short secondary creep stage and may quickly enter the accelerated creep stage, resulting in “plastic flow.” For the soft-hard interbedded rock mass, the soft rock has strong rheological property, and its rheological processes differ as the stress level changes, which is often a complex process with the coexistence of elasticity, plasticity, viscoelasticity, viscoplasticity, etc. The rheological properties of hard rock are relatively weak, but some hard brittle rock masses also show certain rheological state due to various kinds of fracture, joint, bedding, etc. Under lower stress level, these rocks mainly show elastoplasticity, and its creep deformation also increases as the stress level increases. Therefore, for the stability analysis of soft-hard interbedded rock mass, it is necessary to consider both the weak nature and elastoplasticity of the rock. If only its elastoplasticity is considered, inaccurate results may be gained. In order to quantitatively simulate the measured stress-strain-time curve, more flexible and diversified mechanical models should be selected, with full consideration given to the complex mechanical behavior and dual rheological characteristics of the layered composite rock mass.

2. Experimental study on rheological properties of rock
The creep test is an important approach to study the rheological properties of the rock, the results of which are the basis for studies on rheological constitutive model. It is of great significance to invert the known parameters of rheological model via measured test data, and identify unknown rheological model.
In this paper, tri-axial creep tests are performed to study the rheological properties of soft-hard interbedded rock mass.

2.1. Equipment and methods for test
RLW-2000 rock tri-axial rheological testing machine is adopted for indoor creep test, which is composed of axial loading system, confining pressure loading system, servo system, control system, data acquisition system and automatic drawing system, as shown in Figure 1.

![RLW-2000 triaxial rheological test system of rock.](image)

Among them, entire digital servo controller (EDC) is adopted for the control part of axial and confining pressure loading systems, which can adopt the force or deformation control, and can also smoothly switch the control mode during test. The voltage stabilizing system adopts AC servo motor for automatic voltage stabilizing. The deformation measuring device adopts displacement extensometer manufactured by Tektronix from the U.S., including two sets in axial and radial directions, with the relative error of ± 0.5%.

The core used is taken from the soft-hard interbedded rock mass in a certain area, with complex composition from weak carbonaceous marl, shale and hard tufa. The core is made into cylinder standard specimen with the size of Φ55 x 110 mm, with the constant temperature and longtime test performed through the tri-axial creep test. The test axial pressure adopts graded loading, i.e. the maximum load to be applied is divided into several grades based on the instantaneous failure strength obtained from the conventional compression test, and then the load is applied gradually from small to large on the same specimen, with the duration of each load determined according to the strain or stress rate change of the specimen. During the test, the confining pressure shall be kept constant, and the indoor temperature shall be strictly controlled at 25º C. During the test, the computer automatically collects the data of load, deformation and time, and displays the axial deformation-time curve in time.

2.2. Test results
Fig. 2 shows the stress-deformation-time relationship chart of soft and hard cores under tri-axial stress, in which, the confining pressure keeps constant at 2MPa, the axial pressure is gradually increased, the primary load is 14MPa, the load increments are 2.5MPa and 7MPa, and the durations of different loads are 32h and 40h, respectively.
3. Theoretical model and rheological parameters

3.1. Creep theoretical model and failure criterion
Different rocks undergo three stages of creep deformation at different times. For specific rocks, it is necessary to make a brief analysis on the test curve before determining the creep theoretical model. It can be seen from the above creep test results that, under most stress levels, the deformation of hard rock tends to converge gradually over time, which is similar to the strain-time curve of the generalized Kelvin model. For soft rock, the test curve shows that the strain does not converge to a certain value over time, but increases gradually, and this is consistent with the rheological behavior of the Burgers model. In this paper, the Burgers model and the generalized Kelvin model are applied to describe the rheological properties of soft and hard rocks in layered composite rock mass, and the mechanical behaviors of hard rocks after the stress peak enters yield or reaches failure is analyzed in combination with the Mohr-Coulomb shear failure criterion and the pull failure criterion.

3.2. Standard Attention Index
At present, methods for determining rheological parameters based on laboratory test data and curves mainly include regression analysis, optimum separation method, least square method, and curve decomposition method. In this paper, the viscoelastic parameters optimum separation method proposed in literature is applied to calculate the rheological parameters. First, the design variables and objective function are given. The parameters are optimized and separated with parameters to be inverted as the design variables, and the minimum value of sum of the squares of the strain residuals calculated according to the n test data $\varepsilon$ given by the creep test data as the objective function. Therefore, design variables are:

$$X = (E_1, E_2, \eta_1, \eta_2) = (X_1, X_2, X_3, X_4)$$  \hspace{1cm} (1)

The target function is:

$$f(X) = \sum_{i=1}^{n} [\varepsilon(t_i)_c - \varepsilon(t_i)_m]^2$$  \hspace{1cm} (2)

Where, $\varepsilon(t_i)_c$ and $\varepsilon(t_i)_m$ are strain values calculated and tested at $t_i$.

For generalized Kelvin model, the target function is:
For Burgers model, the target function is:

\[ f(x) = \sum_{i=1}^{n} \left[ \frac{\sigma}{E_1} + \frac{\sigma}{E_2} \left(1 - \exp\left(-\frac{E_2}{\eta_1} t_i\right)\right) - \varepsilon(t_i) \right]^2 \]  \hspace{1cm} (3)

To simplify that aforesaid optimization processes, the possible upper and lower limit estimates of the design variables can be given according to analogy based on engineering experience, so as to set up constrain conditions:

\[ a_i \leq X_i \leq b_i \hspace{1cm} (i = 1, 2, 3, 4) \]  \hspace{1cm} (5)

Where, \( X_i \) is the first design variable; \( b_i \) and \( a_i \) are upper and lower limit values of \( X_i \), respectively. The mathematical model established by equations (1), (3), (4) and (5) can be applied to gradually approach the optimized point \( X^* = (E_1, E_2, \eta_1, \eta_2) \) to solve the minimization of the objective function by using the multi-constraint optimization method. \( X^* \) calculated is the Characteristic parameter vector of rock mass to be calculated. According to the above method, the rheological parameters are determined as shown in Table 1:

| Lithology | Model            | \( E_1 \) /GPa | \( E_2 \) /GPa | \( \eta_1 \) / (GPa·h) | \( \eta_2 \) / (GPa·h) |
|-----------|------------------|----------------|----------------|-----------------------|-----------------------|
| Marlstone | Burgers model    | 23.431         | 1.660          | 1769.493              | 43.507                |
| Shale     | Burgers model    | 3.437          | 0.310          | 3623.973              | 129.762               |
| Interlayer| Burgers model    | 1.588          | 0.275          | 121.752               | 8.528                 |
| Tuff      | Modified Kelvin  | 20.002         | 38.603         | 538.635               |                       |

Based on the creep curve of step loading, the rheological parameters are estimated. With the increase of stress level, the instantaneous elastic modulus and viscosity coefficient are gradually increasing, while the viscoelastic modulus is gradually decreasing. With the decrease of stress level, the instantaneous elastic modulus and viscosity coefficient of the rheological parameters obtained by step unloading creep curve are gradually decreasing The viscoelastic modulus increases gradually, and the change rule of the parameters is just opposite to that under the loading condition.

**Table 1. Rheological parameters**

**Figure 3.** The relation between the elastic modulus and viscous coefficient with stress paths.
4. Conclusion
The identification and parameter estimation of rock rheological constitutive model are important problems in rock mechanics theory and engineering practice. In this paper, based on the triaxial compression creep test of rock, the rock mechanics tests are carried out under two different stress paths, i.e. step loading and step unloading. For soft-hard interbedded rock mass, the generalized Kelvin model is use for the hard rock, and the Burgers model is used for the soft rock, so the rheological properties of the layered composite rock can be well described. Different stress states and loading paths have some influence on the rheological behavior of the rock mass. The creep displacement of the rock mass is increased and the lower the confining pressure is, the more obvious the rheological property of the rock mass is, which indicates that the confining pressure has a certain inhibitory effect on the rheology of rock mass.

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