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Experimental investigations of the creep–damage–rupture behaviour of rock salt

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ABSTRACT

The creep–damage behaviour of rock salt, especially in the tertiary creep phase has been rarely investigated. The creep–damage–rupture characteristics of rock salt are studied in this paper by applying Wang's creep–damage model, the experimental results of the triaxial destructive creep–damage tests using quasi-static loading on rock salt specimens are presented, complete creep–damage curves are obtained, and the evolution laws of deformation and damage of rock salt in the primary (transitional), secondary (steady-state) and tertiary (accelerating) phases are deduced. The long-term behaviour of dilatancy of rock salt is investigated according to the dilatancy boundary theory and an approximate long-term dilatancy boundary range is obtained. Finally, the long-term strength of rock salt is evaluated for the test samples. The used model proves to conform well to the test data, including in the tertiary creep–damage phase; it can be suitable for the assessment of collapse, cracking, rupture and other long-term failures, and hence for theoretical basis of design in the underground engineering of gas and oil storage cavern, nuclear waste disposal and other facilities in salt deposit.

1. Introduction

Rock salt creeps very strongly under loads [1]. This is widely accepted as correct in the research on the construction and operation of the salt gas storage cavern as well as the deep geological repositories in rock salt. Safety is very important for salt material exploitation and underground energy storage in salt caverns, as well as nuclear waste disposal in rock salt deposits. In the safety category of such projects the behaviour of strength and deformation as well as tightness of the rock salt and hence the entire cavern is inevitably of concern. This kind of strength or stability behaviour is, of course, not in the conventional sense, but must be related with time. In order to study the rupture behaviour deduced by long-term creep of the rock salt, we can begin from the tertiary creep (accelerating) phase. Although plenty of research works concerned with the creep behaviour in the steady-state phase of rock salt have been carried out, only few reports are, unfortunately, related to the creep behaviour in the accelerating phase, and the evolving mechanisms of creep–damage–rupture of rock salt is to be further deeply investigated. Composite linear or nonlinear rheological medium models were used to attempt to describe the accelerating creep behaviour, but the effectiveness was very limited. Carter et al. [2], Chan et al. [3,4], and Hou et al. [5] proposed creep–damage models by applying damage mechanics of continuum into creep analysis. Zhou et al. [6] carried out damage analyses coupled with the elastoplastic, viscoplastic deformation, obtained a general constitutive relationship that can be used to describe the accelerating creep through to failure of materials; they recently established creep model for rock salt based on fractional derivatives [7]. By referring the fact that salt formations in China are commonly with non-salt interlayers, some authors studied the creep and damage behaviour of bedded rock salt using microscopic methods as well as Cosserat equivalent medium model [8–10], but not concerning the accelerating creep (damage).

We have carried out such research works concerning the creep behaviour in the accelerating stage of rock salt several years ago, proposing a creep–damage model for rock salt which can well demonstrate the rheological damage behaviour at high stress level, and truthfully describe the primary and secondary creep damage at low stress level as well [1]. We used test data from the literatures for verification. Recently, we have systematically carried out triaxial destructive creep–damage tests on rock salt samples in the laboratory using the quasi-static loading strategy. In this paper the test results are used to more deeply investigate the creep–damage–rapture characteristics of rock salt by means of the creep–damage model previously proposed by the author [1].

2. The creep–damage model in brief

The creep–damage model we used is based on the damage mechanics of continuum [1]. Regardless of the fine- or

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Table 1
Outline of the rock salt specimens for the destructive triaxial creep–damage test.

No.	ϕ (mm)	h (mm)	σ_3 (Mpa)	σ_1 (Mpa)							step	t (h)
1	48.60	86.62	5.0	21.5	43.1	53.8					3	25.0
2	49.10	80.98	10.0	21.1	42.2	52.7	62.6				4	25.0
3	48.44	105.22	2.0	10.8	16.2	18.9	21.6	24.4	30.1	38.0	7	75.0
4	48.85	83.32	8.0	21.3	37.3	47.9	58.4				4	22.5
5	48.84	84.53	6.0	21.3	32.0	40.0	48.0	53.2			5	48.2
6	48.09	93.21	4.0	21.6	32.5	40.6	49.4				4	[a]

[a] Data for the first 2 steps lost due to power off.

micro-behaviour from the onset-evolution-interconnection of the cracks, and up to rupture during the process of creep–damage of rock salt, the internal variable-damage factor, and its corresponding rheological deformation are used to demonstrate the creep–damage continuum macro-characteristics of rock salt.

In the creep–damage model, the total creep deformation includes three components: primary creep ε_t, steady-state creep ε_s, and creep induced by damage ε_d, namely

$$\varepsilon = \varepsilon_t + \varepsilon_s + \varepsilon_d \tag{1}$$

where

$$\varepsilon_t = \frac{\sigma}{E}\left[1 - \exp\left(-\frac{G}{\eta}t\right)\right] \tag{2}$$

$$\varepsilon_s = A_1 \exp\left(-\frac{Q_1}{RT}\right)\sigma^n t \tag{3}$$

$$\varepsilon_d = A_2 \exp\left(-\frac{Q_2}{RT}\right)\left(\frac{\sigma}{1-D}\right)^n t \tag{4}$$

and where E is the elasticity modulus, G is the shear modulus, η is the coefficient of viscosity, Q_1 and Q_2 are effective activation energies, σ is the stress, t is the elapsed time, $\{A_1, A_2, n\}$ are material coefficients, R is the universal gas constant, T is the absolute Kelvin temperature temperature, and D is the damage factor, $0 \le D \le 1$.

The damage evolution equation is written as

$$\dot{D} = \left[\frac{\sigma^*}{B(1-D)(1-\langle D - D_a\rangle)}\right]^r \tag{5}$$

where σ^* is the damage equivalent stress, given by

$$\sigma^* = \sigma\left[\frac{2}{3}(1+\nu_0) + 3(1-2\nu_0)\left(\frac{\sigma_m}{\sigma}\right)^2\right]^{0.5} \tag{6}$$

ν_0 is the primary Poisson′s ratio, σ_m is the mean stress, given by

$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3 \tag{7}$$

the symbol $\langle x\rangle$ denotes the "switch function", defined by

$$\langle x\rangle = \begin{cases} x & x \ge 0 \\ 0 & x < 0 \end{cases} \tag{8}$$

B and r are material coefficients, and D_a is the damage accelerating limit.

3. Destructive creep–damage tests of rock salt samples

The rock salt samples were obtained from the borehole Jinzi 1#, Jintan gas storage field in rock salt, Jiangsu province, located at 1050–1070 m under ground level. The major mineral of the cores of rock salt is NaCl. The samples were grey white, partly with dark impurities. Since the rock salt cores had been bored for period, the unloading effect was significant, and so the test specimens were cut and polished with great difficulty. The target size of the cylindrical test specimens was ϕ 50 mm × 100 mm according to the international standard for the rock mechanical tests [11], but the final size was slightly of discrepancy after carefully cutting and polishing, as shown in Table 1.

The stepwise/quasi-static loading destructive creep–damage tests were carried out on the computer controlled triaxial rock shear creep test machine, RLJW–2000. The specimens were carefully mantled with an impermeable viton jacket before installing into the Kármán gauge. After the confining pressure had reached designed value and maintained constant, the axial deviation load was applied. We used multi-staged fast creep test scheme for the creep tests. During one creep test, the confining pressure was maintained constant and the designed axial load was applied in 3–7 steps; once the deformation reached a quasi-steady rate, i.e. the deformation rate increment was nearing steady (the deviation was less than 10%), under the current axial load, the next load step was applied, until the accelerating creep (damage) occurred and failure took place.

The axial stress value at the first load step was set at 30–40% of possible maximum value under the confining pressure. We planned to use 70–80% of the instantaneous strength under the confining pressure as the value of the designed last (maximum) axial stress, but the real load values could be slightly different. During the actual destructive creep tests, accelerating creep/damage took place in the rock salt sample under a certain stress condition, the deformation exceeded the instrument limit and the test was terminated. The other middle load levels were designed according to the principle that the load increments can be larger at lower load levels and the load increments must be smaller when the load level is nearing the accelerating creep/damage stage. A summary of the creep tests is shown in Table 1.

During the tests the confining pressure and the axial load, as well as lateral and axial displacements were automatically recorded, the data consisted 2000–8000 sets for a single test depending on the test time. For example, 5343 sets of test data were recorded for specimen 2# and 8223 sets for specimen 3#. Typical recorded data of the axial (major principal) and lateral (minor principal) strains ε_1, ε_3 and the volumetric strain ε_v, against the stress deviation $\sigma_1 - \sigma_3$ is demonstrated in Fig. 1.

4. Creep–damage–rupture characteristics of rock salt and curve fitting

In accordance with the creep–damage model [1], we made regression analyses for the data obtained from the triaxial destructive creep–damage tests of rock salt specimen, and achieved test fitting parameters, as shown in Table 2. In addition, we used the value of the primary Poison′s ratio $\nu_0 = 0.4$ referring the fact that rock salt creeps very strongly under loads; we set the temperature constant as $T = 295$ K, because the temperature varied not significantly during the test time and the test time lasted not very long (1 to 3 days). Fig. 2 shows the curves of creep deformation data and the corresponding regression results of the rock salt specimens.