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Determination of Damage Constitutive Behavior for Rock Salt Under Uniaxial Compression Condition with Acoustic Emission

Chen Jie[1,2], Zhang Junwei[1,*], Ren Song[1] , Li Lin[1] and Yin Liming[1]

[1]*State Key Laboratory of Coal Mine Disaster Dynamics and Controls, Chongqing University, Chongqing 400030, China*

[2]*Institute of Rock and Soil Mechanics, The Chinese Academy of Science, Wuhan, Hubei 430071, China*

Abstract: The mechanical characteristics of rock salt have an important influence on the safety of the salt cavity. The acoustic emission (AE) technique was used to analyze the generation of microcracks in rock salt under uniaxial compression condition. By monitoring acoustic emission in whole process of stress - strain curve under uniaxial compression test, the damage characteristic of rock salt is obtained. The AE rate-strain curve is able to reflect the damage development process with better consistency evident with the cracks generating. The failure form of rock salt is mainly the shear failure under condition of low loading strain rate. After shear failure, a lot of small crushed particles spread on the surface of the failure surface. A damage constitutive model of rock salt is determined on the basis of acoustic emission characteristics, which could reflect the strength and deformation characteristics before the peak strength.

Keywords: Acoustic emission, damage constitutive model, rock salt, uniaxial compression.

1. INTRODUCTION

To analyze the damage properties of rock salt is very important for use of underground storage of radioactive waste or light hydrocarbons. The main reason for damage failure of the disposal rocks is the generation and development of cracks in excavated disturbed zones (EDZs) along the boundary of cavity and rock [1, 2]. The mechanical properties of rock salts (evaporites with halide components) have been a major focus of study in last few decades [3, 4]. The geomechanical properties of rock salts and salt deposits vary greatly because of different origins, mineralogical components, lithostratigraphic disposition, tectonic history and so on [5, 6]. To improve caverns safety and stability, there is an incentive to test rock salt and better understanding their roles in cavern excavation and the compression damage is also an important failure criterion of rock fracture.

Compressive failure strength is one of the most widely investigated material properties of rock salt. It is now fairly well established that fracture of rock salt under uniaxial compression involves nucleation of microcracks from inhomogenieties or inherent flaws and fissures, which eventually coalesce to cause shear slipping and axial splitting. A stable growth of these microcracks is found to initiate at the onset of dilatancy under uniaxial compressive stress [7-9]. Generally, at the initial stage of the deformation process, the pore volume decreases gradually due to a compaction, this closes the existing microcracks [10, 11]. After the elastic deformation phase, the cracks begin to reopen, or new cracks form because the shear stress increases. This transition from compression, microfracturing, crack closure and reduction in pore volume towards crack reopening, and pore volume expansion takes place with the accumulation of damage zone. The macroscopic fracture plane orientation as indicated by AE source locations show that the macroscopic fracture planes coincide with the direction of the maximum principal stress [12, 13].

Starting from experimental evidence, some uniaxial constitutive equations which describe the damage developing process have been formulated. Some authors who suggested constitutive equations for rock salt, have considered dislocation mechanism and have assumed that during deformation, the volume of the rock salt is incompressible [14-17]. Few papers have reported that a damage potential related to the yield function via a correction term is of the same form as the yield function [18-20]. The development of a constitutive model of damage behavior needs important inputs from dislocation mechanism concepts, and these are applied to predict the microcracks nucleation of rock salt in underground excavations. Material response is specified through the constitutive model and appropriate material parameters are obtained from laboratory tests. The model is based on damage theory and laboratory data together with site geological characteristics to form the basis of the predictive method. As a result, the suitable constitutive model of damage is developed to predict the damage process.

This paper proposes a theoretical approach that combines damage theory with crack growth to model the dynamic

*Address correspondence to this author at the State Key Laboratory of Coal Mine Disaster Dynamics and Controls, Chongqing University, Chongqing 400030, China; Tel: +86-15823308237; Fax: +86-023-65105605;
E-mail: 674998477@qq.com

fracture process of rock specimens subjected to low strain rate under uniaxial compressive loading. More specifically, the model takes into account the rock salt material and AE properties. The damage constitutive model is based on the AE number of fracture-induced defects. The growth of microcracks is controlled by ‘‘wing’’ cracks or tension cracks, from the tips of the isolated inclined pre-existing cracks. When damage parameter reaches a critical value, it is assumed that the microcracks coalesce and cause shear slip.

2. EXPERIMENTAL CONDITIONS AND METHODS

2.1. Experimental Conditions

In order to analyze rock salt acoustic emission characteristics and microcracks development under the uniaxial compression condition and minimize the interference of the impurities, the test specimens are chosen with high purity salt from Khewra salt mine in Pakistan. Test specimens are pink, transparent and compact structure. Its soluble content is about 96.3% ~ 99.8% (soluble substance mainly for NaCl, Na_2SO_4) and the insoluble compositions are mainly argillic minerals. The tests were conducted with cuboid specimens (50 mm ×50 mm in width and 100 mm in length), which were used for observing surface crack propagation under uniaxial compression and monitoring acoustic emission signal.

2.2. Experimental Equipment and Procedure

The main purpose of this experiment was to investigate the behavior of acoustic emission and the damage evolution characteristics under uniaxial compression condition. An AG-I250 electronic precision material testing machine with a maximum axial loading capacity of 1000kN was used to record the applied loads and corresponding displacements. In order to understand how the damage evolution, uniaxial compression tests were done with a constant loading strain rate of about $\dot{\varepsilon}_{cp}$ =2.0 × 10-5s-1, synchronous with the acoustic emission signal monitor in the loading process. DISP series 2 channel/PCI card-two full digital acoustic emission auto monitor produced by the American Physical Acoustics company was used. The threshold was set at 45dB to gain a high signal/noise ratio. Two sensors with frequency sensitivities between 20 KHz to 400 KHz and a 45 dB pre-amplification (AEwin) were used in the AE system. The sensors were fixed on rock surface using gum bands, and vaseline was applied for coupling. Plastic cushions were sandwiched between steel plates and specimen to minimize noise generation due to friction. In order to observe the samples surface cracks development, we need to keep acoustic emission signal monitoring and camera recording at the same time during the loading process. Test devices are shown in Fig. (**1**). All specimens had a same drying process prior to testing, and the tests were carried out at same room temperature.

3. RESULTS AND DISCUSSION

At room temperature, three Pakistani high purity rock salt specimens for uniaxial compression test results are shown in Table **1**. Corresponding stress - strain curve is shown in Fig. (**2**).

3.1. Acoustic Emission Characteristics of Rock Salt Under Uniaxial Compression

Fracture in a quasi-brittle material such as rock involves micro-cracking which generates elastic waves known as acoustic emissions (AE) signals. These transient waves propagate through the medium with very small amplitudes and high frequencies and the AE signals carry information about the source, including location and mechanism defined

Fig. (1). Test equipments.

Table 1. **Results of three cuboid specimens under uniaxial compression conditions.**

Specimens Number	Elastic Limit Stress/MPa	Peak Stress/MPa	Axial Strain at Peak Stress/%	Yong's Modulus /GPa
Salt-1	10.64	34.15	5.53	2.06
Salt-2	9.36	36.01	6.49	2.57
Salt-3	10.32	36.98	6.91	2.41

by mode and magnitude [10]. This definition suggests that the recorded acoustic emissions can be used to determine the rock damage and seismicity process. The process of crack initiation, coalescence and propagation occur with the release of energy which can be recorded as an acoustic signal.

The curvilinear stress-strain relationship, AE rate-strain and AE number-strain are shown in Figs. (**3**, **4**). By combining the AE rate of the salt rock in uniaxial process and the complete stress-strain curve in rock mechanics [21], the stress-strain curve of rock salt in uniaxial compression can be divided into five stages:

Stage 1(OA section): Pre-existing fracture/pore closure-The initial non-linear, downward concave stress–strain relationship at low stress levels is caused by the closure of some primary pores and cracks with increasing compaction. The restoration of artificial cracks from drilling or excavation is also governed by this process [1]. The strain in this stage is about 2% of the total strain. Almost no acoustic emission signal produced at this stage for the internal original crack that has not developed. The pore in the low loading strain rate slowly closed to each other with no new cracks generated.

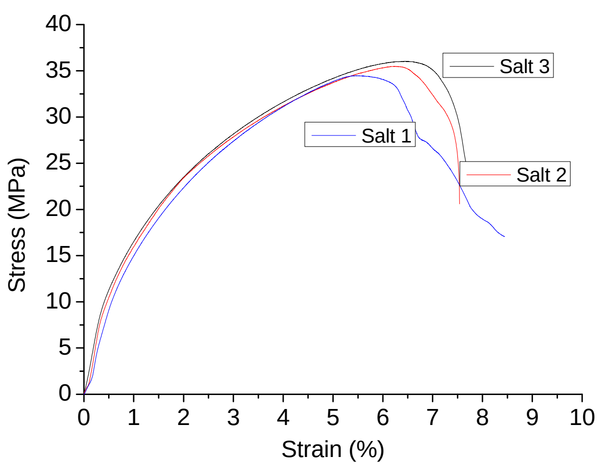


Fig. (2). Stress-Strain curve under unaxial compression.

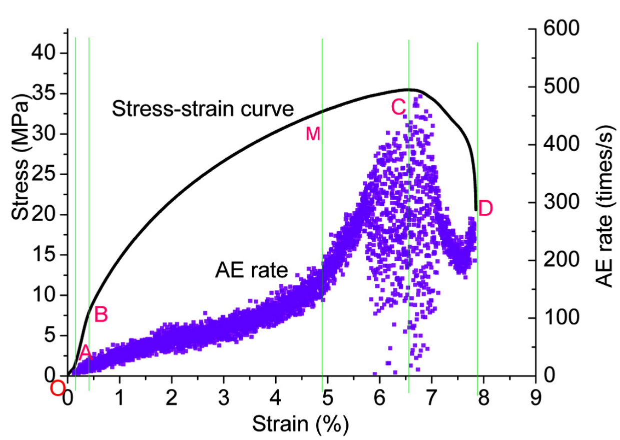


Fig. (3). Damage fracture processes divide under unaxial compression.

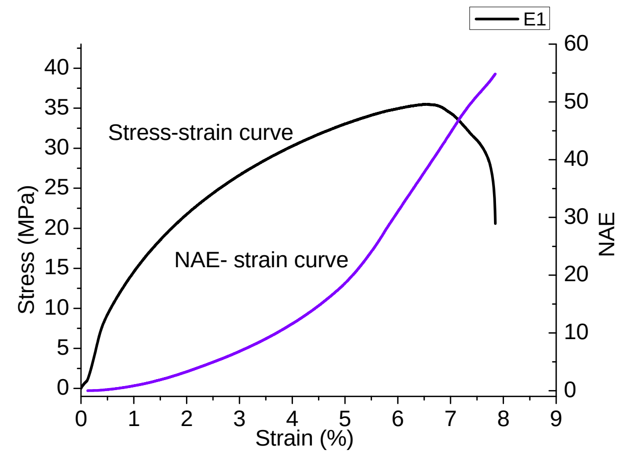


Fig. (4). Relationships of Normalized Accumulative AE number (NAE) and stress with strain.

Stage 2(AB section): Elastic deformation-After the partial closure of the primary cracks, the loading begins with increasing axial stress. From point A, the elastic behaviour dominates the stress–strain relationship. The elastic deformation due to compaction is characterized in all experiments by linear increments in the axial strains. The strain in this stage is about 6% of the total strain. Linear elastic deformation stage, AE signal began to appear in small amount and the AE number slowly increased as the stress increases. The rock salt will cause a little generation of acoustic emission signal because of its own grain features (square crystal) and structural form, intergranular extrusion deformation.

Stage 3(BM section): Plastic deformation with microcracks stable extension-The microcracks start to open and grow. This is characterized by a departure of the strain curves from the elastic behaviour. This stage is referred to as the stable crack growth region, and the strain is about 59% of the total strain. The rock internal crack stable expansion and the speed of crack formation is relatively stable and slow, leading to the AE rate increasing slowly and approximate a linear growth. Paper [22] suggested that in the plastic deformation process, the specimens internal "wing" crack is constantly increasing, which make the AE number stably increase gradually.

Stage 4(MC section): Plastic deformation with microcracks unstable extension-Starting from point M, the AE rate is suddenly increased along with the strain increasing. The rate of increase of axial strains accelerates rapidly as the axial loading increases and the stress reaches the peak strength. The strain is about 6% of the total strain. The stage of plastic deformation micro-crack unsteady expansion, AE rate is increasing fast and the value of AE rate appears to be an obviously fluctuating change. In this stage, the internal cracks in salt fast derived expansion collection and the fractured zone formed damage slip plane so that they produce a large numbers of AEs. This region begins with the plasticity for rock salt at point M, where the AE rate suddenly begins to rapidly increase. The stress here is close to the peak stress and therefore causes the "wing" cracks to begin to gather and form a fracture zone. Point M corresponds to the Kaiser Effect [23] of the AE rate-strain curve and it can be used as a premonition of rock specimens turning into failure. This phenomenon was observed in all specimens under uniaxial compression test and it shows that using Kaiser Effect (point M) to monitor the premonition of salt rock pillar damage in mining will be helpful for the cavern stability.

Stage 5(CD section): Post-failure stage- After reaching the peak strength, the transfixion cracks were formed, the load-carrying capacity decreased rapidly and a significant change is observed on the shape of curve. The AE number further rapidly increases and the maximum AE rate generally appears in this stage with huge fluctuations. When the shear plane is formed, the AE number begins to decrease [22, 24]. The movement of the fracture surfaces prompted a large number of AEs and also generated many secondary tension cracks.

3.2. Fracture Characteristics of Rock Salt Under Uniaxial Compression

In order to further analyze the damage characteristics in the process of uniaxial compression, a High Definition camera was used to record the entire failure process of the salt specimen. The salt specimens surface graphs corresponding to the turning point of the stress-strain curve stages division in uniaxial compressive are shown in Fig. (**5**).

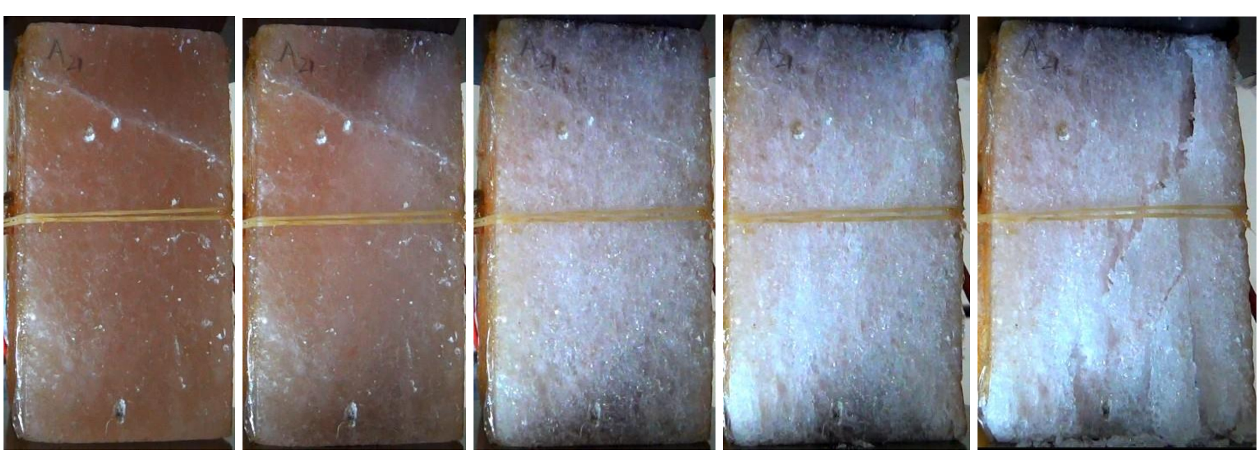
At the uniaxial compression condition and with low loading rate, the failure forms of salt specimens were usually with the combination of the shear failure and tension fracture. The rock color will change with the load increasing because of the special mineral composition and structure of salt rock. The salt specimen was damaged by loading, and the light transmission property obviously changed because of the effect of crack. In the loading process, the light transmission property gradually became weak as the stress increased and the color of the specimen turned gradually from its initial pink to white.

In fact, in condition of low loading strain rate, the eventual destruction of the specimens is by shear slipping face with intense tension cracking. A larger regional piece of rib spalling is also observed at one side of salt specimen. This process accompanied by large number of small sized salt grain peelings and shear sliding surface, has an obvious dislocation, but has not separated shear failure face like the brittle rock.

This deformation mechanism characterized by shear stress and tension stress leads to shear slip with tension cracks. This defines a rock deformation which occurs predominantly at grain level and accordingly causes the polycrystalline rock fragments to slide and rotate. This process increases the pore volume of the cracks. The coalescence of these cracks through various mechanisms results in an increase in the porosity and permeability of the system [25].

4. A DAMAGE CONSTITUTIVE MODEL BASED ON ACOUSTIC EMISSION

Wawersik and Krajcinovic [26, 27] proposed that damage is caused by microcracks and microvoid in the rock material. These microcrack and microvoid cannot bear any stress once formed. Based on this theory, the rock damage model was established by combined Lemaitre’s strain equivalent hypothesis [28]. This theory mainly studies the geometrical characteristic of the initial damage influence on the subsequent damage and pays no attention to the effects that microscopic damage has on macroscopic deformation [29]. In order to deal with convenience, such model cannot be considered as a part of the carrying capacity of material damage, so this intuitive definition is necessary. Some crystalline rock in the compression loads condition mainly focuses on the effects that microscopic damage has on macroscopic deformation. So the load bearing capacity of damaged material cannot be ignored. Therefore ignoring the loading capability of damaged material is not reasonable and cannot reflect the actual situation of rock that softening characteristic gradually turns into hardening characteristic when pressure increases. Therefore, Cao [30] thinks "damage" is the linear elastic stress state transform to nonlinear stress state. This abstract "damage" definition is



A B M C D

Fig. (5). Typical damage fracture procession under unaxial compression with various loading strain rate. The picture of **A**, **B**, **M**, **C**, **D** are corresponding with the point in Fig. (**3**).

not limited to the specific form after the material damage which suggests that the damaged part of the material still take on some stresses and is only a change in the state of stress.

4.1. Definition of Damage Model

On this basis, assume that the damaged rock made up by two parts under the loading stress (i.e. undamaged materials and damaged materials), can bear certain stress. On Fig. (**6**), assume the stress applied to the rock material is σ_i , the corresponding sectional area is *A*, the stress of the intact material part (Shaded part of Fig. **6**) is $\sigma_i^{'}$ and the corresponding bearing area is A' and the stress of the destructive material part (Blank part of Fig. **6**) is $\sigma_i^{''}$, the corresponding bearing area is A'', then the relationship can be expressed as:

$$\sigma_i^{'} A^{'} + \sigma_i^{''} A^{''} = \sigma_i (A^{'} + A^{''}) \tag{1}$$

$$\sigma_i^{'} \frac{A^{'}}{A} + \sigma_i^{''} \frac{A^{''}}{A} = \sigma_i \tag{2}$$

The ratio A''/ A is defined as the rock material damage variable and is equal to Φ . Substituting Φ for the ratio A'/ A, then Equations (1) and (2) can be expressed as:

$$\sigma_i^{'}(1-\Phi) + \sigma_i^{''}\Phi = \sigma_i \tag{3}$$

Equation (3) which is a new type of rock damage model was established by Cao [30] , the first step of building the rock damage constitutive model is to set up the relationship for strain with $\sigma_i^{'}$ and $\sigma_i^{''}$.

4.2. The Definition of Uniaxial Compression Effective Stress and Damage Stress

In order to establish the rock damage constitutive relationship in low loading strain rate under uniaxial compression conditions, the following assumptions are made:

(1) Stress-strain relationship in uniaxial compression has a linear elastic relationship before the rock is damaged. This is represented by:

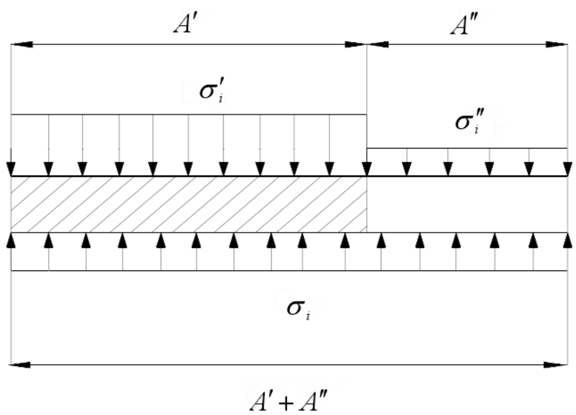


Fig. (6). The damage model for rock.

$$\sigma^{'} = E\varepsilon \tag{4}$$

where E is elastic modulus and ε is strain.

(2) Rock materials become friction material after damaged and its stress condition satisfies the Mohr - Coulomb criterion as follow [30]:

$$\sigma^{''} = 2c\tan\alpha \tag{5}$$

where $\alpha = \pi/4 + \varphi/2$; c is the cohesion and φ is the internal friction angle.

Substituting Eq. 4 and Eq. 5 into Eq. 3, Equation (6) can be rewritten by:

$$\sigma = E\varepsilon(1-\Phi) + 2cD\tan\alpha \tag{6}$$

4.3. The Definition of Damage Evolution Equation based on Acoustic Emission

The failure process of rock salt in uniaxial compression mainly shows grain damage and grain slip. When the strain energy which agglomerates in the failure process is quickly released, it appears as acoustic emission signals. So we can define the total grain number of failure area A is N, and it will produce Ne AE number reached peak strength. We can also define the destroyed grain number of failure surface is n, and it will produce NAE number, then the rock uniaxial damage variable D can be defined as:

$$\Phi = \frac{A^{'}}{A} = \frac{n}{N} = \frac{n_e}{N_e} \tag{7}$$

As shown in Fig. (**5**), accumulative AE number has an approximation index relationship with strain hypothesis:

$$n_e = p\exp(b\varepsilon) + q \tag{8}$$

Where ε is specimen axial strain; *p* and *q* are constants.

According the uniaxial compression and AE initial conditions, we can found that at the elastic deformation stage(AB section) almost no AE signal, so at the point B (the strain ε_0) of Fig. (**3**) the $n_e = 0$; And at the point D (the strain ε_f) of Fig. (**3**), $n_e = N_e$ the accumulative AE number $n_e = N_e$. So the initial conditions can describe as:

$$n_e = \begin{cases} 0 & (\varepsilon = \varepsilon_0), \\ N_e & (\varepsilon = \varepsilon_f). \end{cases} \tag{9}$$

Where ε is specimen axial strain; ε_0 is the initial strain of AE signal begin to generating (the strain at point B of stress-strain curve of Fig. (**3**); ε_f is the total strain when the specimen is completely destroyed (the strain at point D of stress-strain curve of Fig. (**3**); n_e is accumulative AE number; N_e is total accumulative AE number when the strain reach point D of Fig. (**3**).

Substituting the initial condition of Eq.9 into Eq.8, one gets

$$p=\frac{N_e}{\exp(b\varepsilon_f)-\exp(b\varepsilon_0)}\ ,\ q=\frac{-N_e\exp(b\varepsilon_0)}{\exp(b\varepsilon_f)-\exp(b\varepsilon_0)} \tag{10}$$

Substituting Eq.10 into Eq.8, one gets

$$n_e=\frac{\exp[-b(\varepsilon_f-\varepsilon)]-\exp[-b(\varepsilon_f-\varepsilon_0)]}{1-\exp[-b(\varepsilon_f-\varepsilon_0)]}N_C \tag{11}$$

Assumption the AE number has a linear relationship with the number of rock grain fracture, then:

$$n=\beta n_e;\ N=\beta N_e;(\beta\geq 1) \tag{12}$$

The damage evolution equation can be written as follows:

$$\Phi=\frac{n_e}{N_e}=\frac{n_e}{N_e}=\frac{\exp[-b(\varepsilon_f-\varepsilon)]-\exp[-b(\varepsilon_f-\varepsilon_0)]}{1-\exp[-b(\varepsilon_f-\varepsilon_0)]} \tag{13}$$

4.4. The Definition of Damage Constitutive Equation Based on Acoustic Emission

The complete stress-strain curve, Fig. (**3**), shows that: At stage OB, no new cracks generate in the process of axial strain increasing linearly, which obey the elastic constitutive model. At stage BD, new cracks generation induced damage. According to the new definition of rock damage model of Equation 6, the damage evolution presented in Equation 13, and also considering the rock material, the physical and mechanical characteristics of the rock can be defined by the rock uniaxial damage constitutive equation. Then the total constitutive model can be described as follows:

$$\sigma=\begin{cases}E\varepsilon \\ b_1E\varepsilon\dfrac{1-\exp[-b(\bar{\varepsilon}_f-\varepsilon)]}{1-\exp[-b(\bar{\varepsilon}_f-\varepsilon_0)]}+b_2 2C\tan\alpha\dfrac{\exp[-b(\bar{\varepsilon}_f-\varepsilon)]}{1-\exp[-b(\bar{\varepsilon}_f-\varepsilon_0)]}+b_3M\end{cases} \tag{14}$$

$$0<\varepsilon<\varepsilon_0$$

$$\varepsilon_B<\varepsilon<\bar{\varepsilon}_f$$

$$M=\frac{\exp[-b(\varepsilon_f-\varepsilon_0)]}{1-\exp[-b(\varepsilon_f-\varepsilon_0)]} \tag{15}$$

Where b_1, b_2 and b_3 are constants; $\bar{\varepsilon}_f$ is the total strain correction value, $\bar{\varepsilon}_f=\lambda\varepsilon_f$, λ is constants for the specimen that is not completely destroyed but the loading stopped.

Equation 14 is made up by two parts. Part 1 is used to describe elastic deformation, and the strain is $0<\varepsilon<\varepsilon_0$. Almost no new cracks are generated in this elastic stage. The second part is used to describe plastic deformation, and the strain is $\varepsilon_0<\varepsilon<\bar{\varepsilon}_f$, damages begin to appear in specimen and evolution gradually expands.

According to the results of rock salt uniaxial compression acoustic emission test in the third section, the initial parameters of Equation 14 (b, b_1, b_2, ε_0, $\bar{\varepsilon}_f$, c, φ) can be determined. Theoretical curve is shown in Fig. (**7**). The damage constitutive equation based on acoustic emission can well reflect the rock stress-strain characteristics in rock uniaxial damage process.

Fig. (**7**) shows that the damage constitutive equation can well describe stress - strain feature before peak strength in low loading strain rate, but it is not good enough to reflect the specimen failure process after uniaxial peak strength. After reaching the peak strength, the transfixion cracks were formed, the load-carrying capacity decreased rapidly and a significant change is microcracks unstable extension. The variation of acoustic emission signals after peak intensity in Figure 3 can be further proof of this phenomenon. So it is hard to find a damage constitutive model to describe stress - strain feature after peak strength.

CONCLUSIONS

According to the rock salt uniaxial compression test combined with monitoring parameter change rule of acoustic emission and the stress - strain curve features, the uniaxial damage characteristic of rock salt is obtained. The AE rate change characteristics in uniaxial compression failure process are analyzed and the rock damage constitutive equation based on acoustic emission characteristics is suggested.

The plastic strain at microcrack steady expansion stage takes up over 50% of the whole strain process in uniaxial compression process. This is totally different from brittle rock. In plastic deformation stage, with the microcracks stable expansion, AE rate is obviously linear in growth and has a better consistency of the strain change. After crack unsteady expansion, it produces a large number of acoustic emission signals fully reflecting shear failure area still with cohesive force.

From the NAE - strain curve and strain - stress curve, it is known that the number of AEs showed obvious regularity with uniaxial damage increment in the rock uniaxial damage process. A damage constitutive equation is established on the basis of relationship between AEs number and strain which

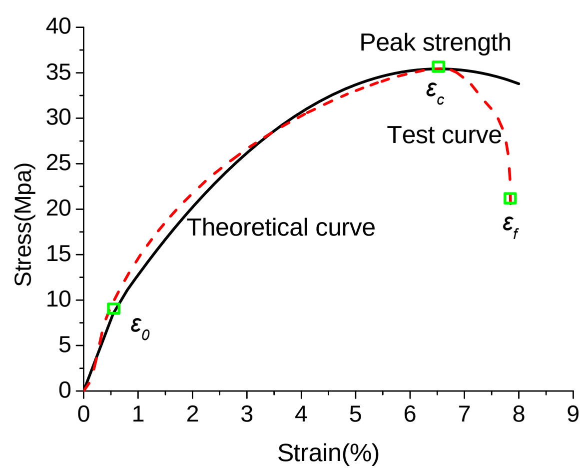


Fig. (7). The stress-strain curve.

can well reflect the stress - strain characteristic before reaching peak strength in the uniaxial compression test but cannot reflect failure characteristics of the post-failure stage.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGMENTS

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