Mechanical Property Experiment and Damage Statistical Constitutive Model of Hongze Rock Salt in China

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ABSTRACT

In order to research the mechanical properties of rock salt in Hongze Zhaoji mine lot of Jiangsu, mechanical tests such as uniaxial compression and triaxial compression of equal confining pressure are taken for the MTS815 rock servo testing machine with the analysis on the experimental results. According to the halite deformation characteristics and taking rock plastic strain as the infinitesimal statistical distribution variable, a proportionality coefficient which could reflect the bearing capacity of the broken part of the rock is introduced with the construction of the damage statistical constitutive model which could reflect the strain hardening characteristics of the rock. Test data is adopted for its verification. It is indicated by the research that the bearing capacity of the infinitesimal broken part of the rock salt under uniaxial compression is very small and can be neglected; while it is very big under high confining pressure and cannot be neglected. In addition, the model proposed by this paper could reflect the entire breaking process of the rock salt sample well.

KEYWORDS: rock salt; mechanical property; experimental study; constitutive model

INTRODUCTION

Salt rock is a special kind of soft rock with advantages of compact structure, low porosity, small permeability, and big plastic deformation capacity. The development of rock salt can not only provide industrial salt, but also its formed underground salt cavern can become good reservoir for nuclear waste, crude oil, and natural gas if mined properly. Due to the important position of salt rock in the underground energy storage, many experimental researches have been carried out by scholars at home and abroad for its creep characteristics in recent years. However, the data on salt rock mechanical feature experiment is still in a lack compared with other rocks.

In describing the constitutive model study of mechanical properties of rock salt, Munson[1], Aubertin[2], Hunsche[3] and other scholars have established the rock salt creep constitutive equation to describe the creep response of rock salt based on the endochronic theory. Weidinger[4] and other scholars have established a complex model to describe the creep features of rock salt based on the microstructure and deformation physical mechanism of rock salt. Fokker[5] have conducted groundbreaking researches on the nonlinear creep equation of salt rock based on numerous conclusion of the mechanical properties of salt rock with experimental analysis and digital model description of the creep dilatancy. Fossum[6], Chan[7] and other scholars have proposed an MDCF of salt rock creep and damage fracture, which takes mechanisms such as the deflection creep, shear damage, damage tensioning and damage rehabilitation of the salt rock into account for satisfactory description of the creep damage features of salt rock. In general, the result is satisfactory in describing the rheological properties of salt rock with these models. However, they are with the disadvantages of complicated model forms and numerous parameters. For example, 42 experimental parameters shall be determined for a representative MDCF model. Therefore, it is very difficult to obtain the accurate model parameters from the testing result. Besides, only the researcher himself could make good use of these models, which greatly restricts their application in practical projects.

Although studies have been conducted for the energy storage and waste disposal of rock salt from many aspects, the short-term strength of rock salt and its creep characteristics research are still restricted in the constitutive analysis of visco-elasticity plasticity with incomplete study on the damage features of the salt rock. Therefore, this paper conducts study on the mechanical properties of rock salt and its damage statistical constitutive model, so as to provide reference for the rock salt solution mining and cavern stability analysis.

EXPERIMENTAL OVERVIEW

Sample collection

The rock salt sample used for the test is taken from Hongze Zhaoji mine lot of Jiangsu with the burial depth of about 2000 meters. Since rock salt is easy to be damaged, deliquesced and weathered during transport, to lead to the change of the mechanical properties of the sample. Therefore, when the rock core is drilled up, it should be packed and sealed immediately with cling film and tape to prevent efflorescence and deliquescence. Then the packaged sample should be put into the core groove to prevent damage of the sample during transport.

Preparation of the test piece

According to the requirements of the rock mechanics test standard, all the test pieces shall be processed into cylindrical standard pieces with the diameter of 50mm and the height of 100mm. Due to the restriction of the sampling cost, core intact rate, and acceptability of the test pieces, 6 qualified test pieces are processed with 3 of which used for uniaxial compression test and the rest for triaxial compression test.

Test equipment and procedures

In order to research the mechanical properties of rock salt, uniaxial compression test and triaxial compression test of equal confining pressure are conducted respectively for the rock salt samples, which shall be completed in the MTS 815 rock material test machines with the adoption of Φ50mm × 100mm cylinder standard samples.

Uniaxial compression test procedure is as follows: pressure head is added to both ends of the cylindrical sample with the installation of strain sensor, then it should be placed in the pressure chamber for axial pressure until it is damaged. The load and strain value of the sample in the entire test process shall be recorded.

Triaxial compression test procedure is as follows: pressure head is added to both ends of the sample with the sealing of seal cartridge and the installation of strain sensor, then it should be placed in the pressure chamber. When the sample installation is completed, the lateral pressure and axial pressure shall both be applied at the loading speed of 0.05MPa per second until it reaches expected lateral pressure which shall be maintained constant in the entire testing process. Axial load at the loading speed of 0.5 to 1.0MPa per second shall be applied until the sample is completely damaged. The damage load and stress - strain curve should be recorded.

TEST RESULTS AND ANALYSIS

Test result

Uniaxial compression test. The relation curve of uniaxial stress of the rock - strain can be obtained by the test as shown in Fig.1. According to the experimental data and the stress - strain curve, the result of the uniaxial compression can be obtained as shown in Table 1 below.

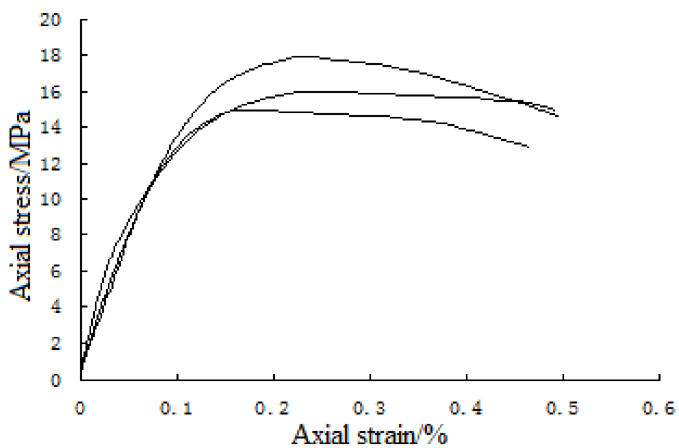


Figure 1: Uniaxial compression stress - strain curve of the salt rock sample

Table1: Test result of uniaxial compression of the salt rock sample

Sample No.	Uniaxial compressive strength(MPa)	Peak strain (%)	Elastic modulus (GPa)	Poisson's ratio

1#	14.95	0.165	9.21	0.324
2#	16.00	0.242	8.63	0.281
3#	17.88	0.230	8.52	0.289
Mean	16.28	0.212	8.79	0.298

As can be seen from Table 1, the discreteness of each mechanism index of the 3 rock salt samples under uniaxial compression is relatively small. The means are taken as the basis for follow-up analysis for the convenience of problem handling.

Triaxial compression test of equal confining pressure. Comparison analysis with the triaxial compression test result is conducted (the confining pressure levels of triaxial test are 5MPa, 10MPa, and 15MPa with each confining pressure level corresponding to a test piece). The stress - strain curve of the entire process of rock salt sample under each confining pressure is shown in Fig.2, and the test result of it is shown in Table 2.

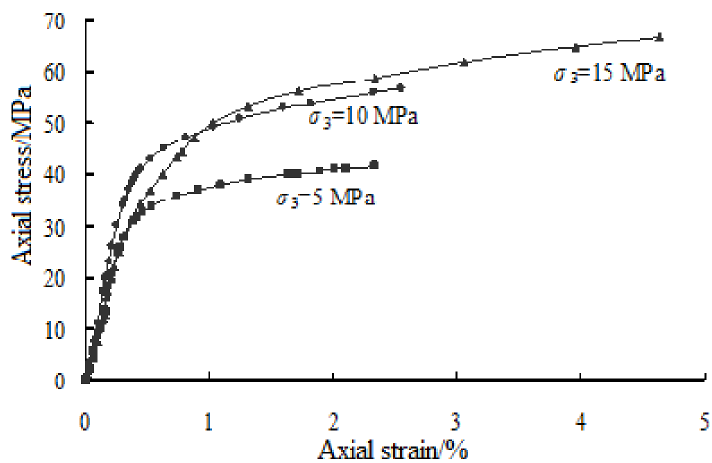


Figure 2: Triaxial compression axial stress - strain curve of the salt rock

Table 2: Test result of triaxial compression of the rock salt

Confining pressure (MPa)	Peak stress (MPa)	peak stain (%)	Elastic modulus (GPa)
5	42.32	2.37	9.32
10	56.70	2.61	13.49
15	66.57	4.78	11.02

It can be seen from Table 2 and Fig. 2 that the strength of salt rock and its deformation features are closely related with the confining pressure it bears.

Strength characteristics of rock salt

It can be seen from Table 1 that the strength of rock salt under uniaxial compression is very low to be only 16.28MPa, indicating that rock salt belongs to the soft rock. With the increase of confining pressure, the strength of rock salt will be increased quickly as well. When the confining pressure reaches 15MPa, it will be 66.57MPa, which means that the increase of confining pressure could greatly improve the strength of rock salt. This is because that the confining pressure could restrict the implementation of internal cracks of the rock salt to prevent relative slippage among the particles, so as to improve the strength of the rock salt. The relation of the strength and confining pressure of rock salt in this test is shown in Fig.3.

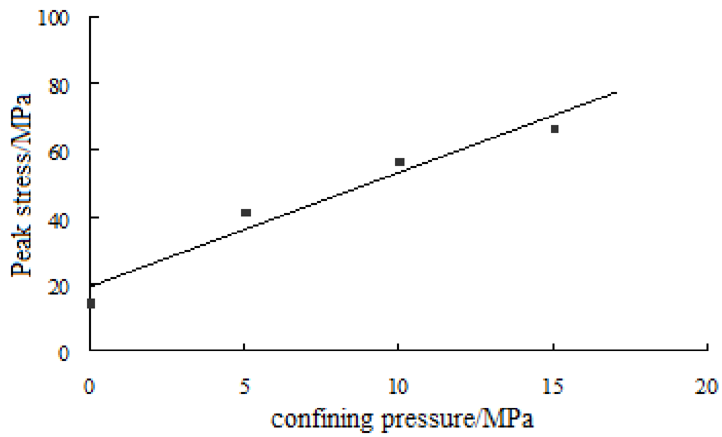


Figure 3: Peak stress distribution figure of rock salt under different confining pressures

The Mohr-Coulomb criterion represented by the principal stress[8] can be expressed as:

$$\sigma_s = A\sigma_3 + B \qquad (1)$$

Where $A = \dfrac{1+\sin\varphi}{1-\sin\varphi}$, $B = \dfrac{2c\cos\varphi}{1-\sin\varphi}$, c and φ refer to the cohesion and internal friction angle of the rock respectively.

As can be seen from Fig. 3, the strength of the rock salt will be increased with the increase of the confining pressure, showing the approximately linear relationship basically in line with the Mohr-Coulomb criterion. Relevant data in Table 1 and Table 2 are put into the formula (1) for regression analysis for the obtaining of parameters A and B, so as to get the cohesion and internal friction angle of the salt rock by using formula (2).

$$\varphi = \arcsin\frac{A-1}{A+1}; \quad c = \frac{B(1-\sin\varphi)}{2\cos\varphi} \qquad (2)$$

It can be calculated by formula (2) that the cohesion and internal friction angle of the rock salt in the test are c = 5.68MPa, φ = 32.4 °respectively.

Deformation characteristics of the rock salt

The photograph of damaged rock salt under uniaxial and triaxial compression is shown in Fig. 4. It can be seen from Fig. 4 that the damage form of the rock salt under uniaxial and triaxial compression is different, which is mainly in lateral tension splitting damage under the uniaxial compression with the occurrence of splitting damage face parallel to the axis.

(a) uniaxial damage

(b) triaxial damage

Figure 4: Photograph of the damaged salt rock

It is because of the low tensile strength of the rock salt that is smaller than the horizontal tensile stress caused by the axial compression; while the damage form of rock salt is mainly lateral expansion damage under triaxial compression with no distinct splitting face, which is because of the confining pressure that greatly restricts the generation and development of internal cracks of the rock salt with the prevention of relative slippage among crystal particles of the rock salt[8], so as to improve its plastic deformation capability.

As can be seen from Fig.1 and Fig.2, the stress - strain relationship of rock salt in low stress state is linear whether under uniaxial or triaxial compression, which means that rock salt is with certain elastic deformation capacity; when the axial stress exceeds a certain value, the stress - strain curve begins to deviate from the linearity. This is because of the different strength of crystal particles in the rock salt sample. With the continuous increase of the axial stress, the weak-gel part of the crystal particles in the rock salt sample will be broken first to lead to the dislocation slippage of the crystal particles for the occurrence of plastic deformation, resulting in the deviation of linearity of the stress – strain curve of the rock sample. If there is no confining pressure or the confining pressure is relatively low at this time, the dislocation slippage (plastic deformation) among the crystal particles will continue to be developed with the increase of the axial stress, and its slipping scope will gradually be expanded from low-strength regions to high-strength ones with the enlargement of the sliding face, so as to form the macroscopic fracture plane finally to lead to overall weakening of the rock sample and the reduction of axial bearing capacity for the occurrence of strain softening phenomenon; if the confining pressure is relatively high, the crystal particles with dislocation slippery will be moved to new positions and be squeezed and compacted due to the high confining pressure[9], and the sliding resistance will be increased. If the particles are to go on slipping, the plastic deformation will be produced and sliding area will be enlarged continuously, which requires constant axial stress increase. Therefore, the strain hardening phenomenon will occur for the rock salt under relatively high confining pressure.

In fact, the plastic deformation of rock salt sample is a macroscopic reflection of its internal crystal slippage and deformation, while its internal crystal particle slippage is directly related to the stress state of the rock sample, which means that the deformation and damage process of rock sample under the loading effect is a continuous development process of plastic deformation. Therefore, the plastic strain of the rock sample can be applied to describe its deformation and damage process.

SALT ROCK STATISTICAL DAMAGE CONSTITUTIVE MODEL

The establishment and analysis of the damage model

Damage mechanics is an effective means for the study of rock constitutive relation. In recent years, the introduction of statistical damage theory[10~14] has led to the great breakthrough of rock constitutive relation research.

It is assumed that the infinitesimal strength of rock is in line with the Weibull distribution, its probability density distribution function will be [10]:

$$P(\varepsilon_p) = \frac{m}{\varepsilon_0}\left(\frac{\varepsilon_p}{\varepsilon_0}\right)^{m-1} \exp\left[-\left(\frac{\varepsilon_p}{\varepsilon_0}\right)^{m}\right] \tag{3}$$

where $P(\varepsilon_p)$ refers to the infinitesimal strength distribution function of the rock, ε_p refers to the distribution variable of the randomly distributed infinitesimal strength, *m* and ε_0 refer to the distribution parameters.

The rock damage variable *D* is defined as the ratio of the damaged rock infinitesimal number under one certain loading effect n and the total undamaged infinitesimal number *N*, namely

$$D = \frac{n}{N} \tag{4}$$

When it is loaded to the level ε_p, the damaged infinitesimal number will be

$$n(\varepsilon_p) = \int_0^{\varepsilon_p} NP(x)dx = N\left\{1 - \exp\left[-\left(\frac{\varepsilon_p}{\varepsilon_0}\right)^m\right]\right\} \tag{5}$$

Put formula (5) into formula (4), then

$$D = 1 - \exp\left[-\left(\frac{\varepsilon_p}{\varepsilon_0}\right)^m\right] \tag{6}$$

It is assumed that the infinitesimal of rock is in line with the Hooke's law before damaged, and it cannot bear any stress after damaged. According to the equivalent strain hypothesis, the rock constitutive relation for the generation of damage[10] can be obtained as

$$\sigma_1 = E\varepsilon_1(1 - D) + 2\nu\sigma_3 \tag{7}$$

Where, E represents the elastic modulus, and υ represents Poisson's ratio.

Formula (7) is based on the assumption that the rock infinitesimal is without bearing capacity, while it is actually still with certain bearing capacity though being lowered after the damage. Therefore, formula (7) can only describe the rock damage process under the strain softening situation rather than the strain hardening situation. As can be seen from Fig. 2, strain hardening features have already shown by the rock sample in the confining pressure of more than 5MPa. In order to describe the strain hardening features of the rock sample better, formula (7) is required to be improved.

Provided the actual part losing bearing capacity among the damaged n rock infinitesimal takes the proportion of α under a certain stress level, the infinitesimal number really losing bearing capacity will be αn, and the rest (1-α) n infinitesimal can be considered undamaged which are still in line with the Hooke's law. The equivalent pressure borne by n rock infinitesimals that are to be damaged will be borne by the undamaged (1-α) n infinitesimals with the rest αn ones having no bearing capacity. So the equivalent damage variable of the improved rock infinitesimal will be

$$D' = \frac{\alpha n}{N} = \alpha\left\{1 - \exp\left[-\left(\frac{\varepsilon_p}{\varepsilon_0}\right)^m\right]\right\} \tag{8}$$

Taking formula (8) into formula (7), and replacing the equivalent damage variable D' with the damage variable D, then the improved constitutive relation [11,12] will be

$$\sigma_1 = E\varepsilon_1\left\{\alpha \exp\left[-\left(\frac{\varepsilon_p}{\varepsilon_0}\right)^m\right]+1-\alpha\right\}+2\nu\sigma_3 \tag{9}$$

It can be seen from formula (9) that the key point for the determination of this constitutive equation lies in the determination of the random distribution variable of rock infinitesimal strength ε_p, scale factor α, and Weibull distribution parameters of m and ε_0.

The traditional rock statistical damage constitutive model usually takes the rock axial strain or damage criterion [13,14] as the infinitesimal statistical distribution variable, while it can be seen from the analysis ahead that it is more reasonable to describe the damage process of rock sample under the loading effect with its plastic deformation amount. Therefore, the infinitesimal statistical distribution variable of traditional model is improved by this paper for better reflection of the damage process of the rock salt with the attempt to distribute the variables randomly taking the axial plastic strain of the rock sample as the rock infinitesimal strength.

Providing the elastic modulus of the rock sample is E, the axial stress and strain tested at the same stress level should be $\sigma_1^{'}$ and $\varepsilon_1^{'}$ respectively. The rock sample has been damaged or has been with plastic deformation at this time, so the tested axial strain $\varepsilon_1^{'}$ is composed of the elastic strain and plastic strain, the latter of which can be calculated by the following formula [15]:

$$\varepsilon_p^{'} = \varepsilon_1^{'} - \frac{\sigma_1^{'} - 2\nu\sigma_3}{E} \tag{10}$$

where E and ν refer to the elastic modulus and Poisson's ratio respectively, and σ_3 represents the confining pressure.

Taking the axial plastic strain of the rock salt sample as the randomly distributed variable of rock infinitesimal strength in formula (9), namely, $\varepsilon_p = \varepsilon_p^{'}$, then

$$\varepsilon_p = \varepsilon_1^{'} - \frac{\sigma_1^{'} - 2\nu\sigma_3}{E} \tag{11}$$

Taking formula (11) into formula (9), and making $\varepsilon_1^{'} = \varepsilon_1$, the rock sample statistical damage constitutive model based on plastic strain established by this paper can be obtained.

Studies by Lai Yong and other scholars [16] have showed that when the stress state of the rock is below the elastic limit point or the damage threshold point, the damage variable of the rock will be very small. Therefore, this paper takes the stress-strain of rock salt sample as the linear relationship before the elastic limit point for the convenience of dealing with the issue.

Although ZHANG and other scholars [10] have proposed a method to determine Weibull distribution parameters in accordance with the slope of o at the stress - strain curve peek of the rock, which is with the advantages of simple parameters and clarified physical significance, it is only suitable for the strain softening features of the rock rather than the strain hardening conditions. Therefore, the constitutive formula is adopted by this paper to determine the model parameter with the method of linearization processing [14]. Formula (9) has to be deformed with the taking of logarithm for twice, then

$$\ln(-\ln\frac{\sigma_1 - 2\nu\sigma_3 + \alpha E\varepsilon_1 - E\varepsilon_1}{\alpha E\varepsilon_1}) = m\ln\varepsilon_p - m\ln\varepsilon_0 \qquad (12)$$

Make $y = \ln(-\ln\frac{\sigma_1 - 2\nu\sigma_3 + \alpha E\varepsilon_1 - E\varepsilon_1}{\alpha E\varepsilon_1})$, $x = \ln\varepsilon_p$, $b = -m\ln\varepsilon_0$, then formula (12) can be turned into

$$y = mx + b \qquad (13)$$

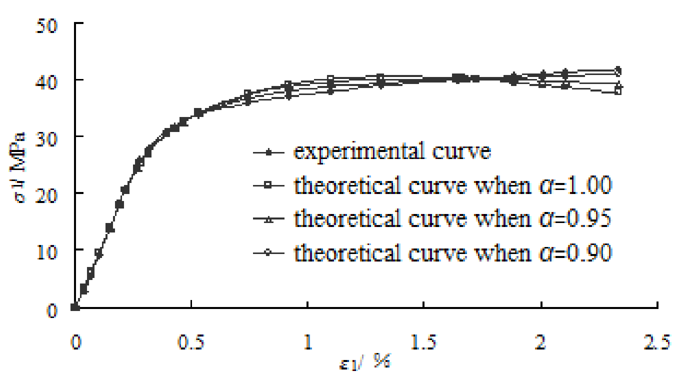
Where, m refers to the slope of the line, and b is the intercept, then

$$\varepsilon_0 = \exp(-b/m) \qquad (14)$$

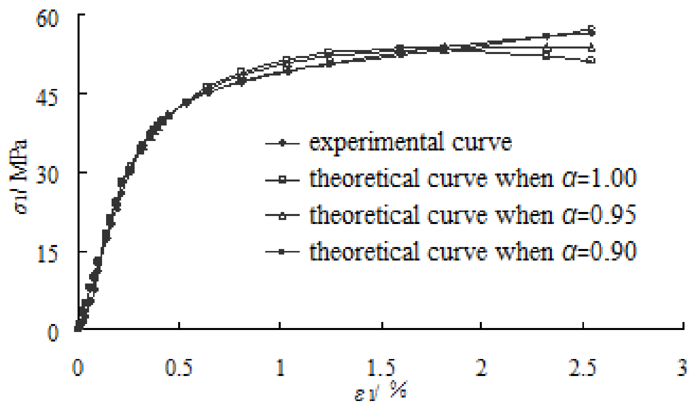
It can be seen by formula (12) to formula (14) that as long as the value of scale factor α is determined, the Weibull distribution parameter m and ε_0 values can be obtained in accordance with the testing data, so as to get the rock sale damage statistical constitutive equation. Different values can be artificially set for the scale factor α for the comparative analysis of the theoretical curve and experimental curve under the different scale factors for the getting of its reasonable value.

Validation of the damage model

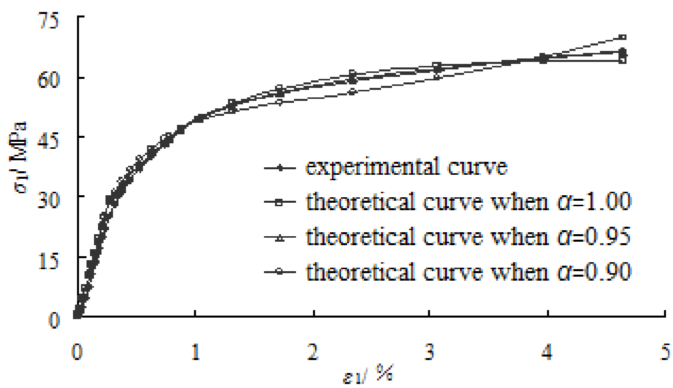
As for triaxial compression test, the scale factors of 1, 0.95 and 0.9 are taken by this paper for calculation. Take the testing data of the rock sample under each confining pressure as the different scale factor into formula (12) to (14) to get the Weibull distribution parameter m and ε_0 under different values of the correction factor, then take the scale factor α and the corresponding *m* and ε_0 values into the model of this paper to get the triaxial compression stress - strain theoretical curve of the salt rock. The theoretical curve of this paper and the experimental curve are compared as shown in Fig. 5.



(a) σ_3=5MPa



(b) σ_3=10MPa



(c) σ_3=15MPa

Figure 5: Comparison diagram of the theoretical curve and experimental curve

As can be seen from Fig.5, if it is without consideration of the bearing capacity of the damaged part of the salt rock infinitesimal or the scale facto of α=1, the theoretical curve should show the certain strain softening characteristics; while when the proper value of the scale factor α is taken, the theoretical curve will show strain hardening characteristics, which is more consistent with the experimental situation. It means that the bearing capacity of the damaged part of the salt damage statistical constitutive model cannot reflect the strain hardening characteristics of the rock salt, which also indicates that the confining pressure is one of the extremely important factor s that affects the level of bearing capacity of the damaged rock. As for the triaxial compression test of the salt rock whose confining pressure is 10MPa and 5MPa, the optimal value of the scale factor is about 0.90, while that is about 0.95 for the test whose confining pressure is 15MPa. In general consideration of the three groups of tests, the scale factor of α=0.92 is finally taken for the reprocessing of the theoretical curve in Figure 5. When α=0.92, the theoretical curve and experimental curve of the triaxial compression are compared as shown in Fig. 6 with the values near the curve representing the confining pressure values.

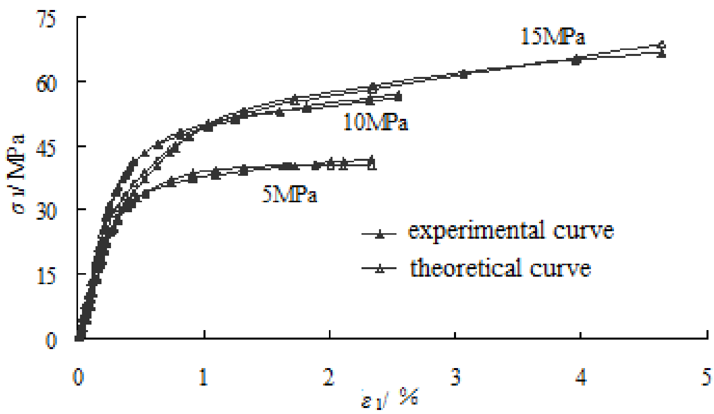


Figure 6: Comparison diagram of the theoretical curve and experimental curve of the triaxial compression when α=0.92

As can be seen from Fig. 6, When the scale factor α=0.92, the theoretical curve and the experimental curve under each confining pressure are very close with high fitting precision. The statistical damage constitutive model based on plastic strain established by this paper could reflect the strain–stress relation and damage process of the salt rock under complex stress state.

CONCLUSION

(1) Uniaxial compressive strength of rock salt is relatively low and it belongs to soft rock with the strain softening features shown under uniaxial compression; the strength and deformation capability of the rock salt can be improved rapidly with the increase of the confining pressure under triaxial compression. When the confining pressure is greater than 5MPa, the strain hardening characteristics will be shown by the rock salt.

(2) The damage formation is different for the rock salt under uniaxial and triaxial compression, which mainly takes the lateral tensile splitting damage under the uniaxial compression, and takes the lateral expansion damage under the triaxial compression without obvious fracture plane.

(3) The bearing capacity of the damaged part of the rock sale infinitesimal is very small and can be neglected under uniaxial compression, while the capacity is relatively large and cannot be ignored under high confining pressure, which indicates that the confining pressure is one of the major factors that may affect the bearing capacity of the damaged rock.

(4) Under the circumstance of insufficient statistical damage constitutive model of traditional rock, the paper takes the plastic strain of the rock as the infinitesimal statistical distribution variable along with the introduction of a scale factor with certain bearing capacity that could reflect the damaged part of the rock, to establish a rock statistical damage constitutive model. In case of triaxial compression, the theoretical curve and the experimental curve is relatively close with high fitting precision when the scale factor is α = 0.92, which indicates that the model proposed by this paper could reflect the stress - strain relationship of the rock salt and the characteristics of its damage process as well as strain hardening well.

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