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Study on the mechanical properties test and constitutive model of rock salt

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Abstract. In order to study the mechanical properties of rock salt, triaxial compression tests under different temperatures and confining pressure are carried out on rock salt specimens, the influence of temperature and confining pressure on the mechanical properties of rock salt was studied. The results show that the temperature has a deteriorative effect on the mechanical properties of rock salt. With the increase of temperature, the peak stress of rock salt decreases visibly; the plastic deformation characteristics become much obvious; the internal friction angle increases; while the cohesion strength decreases. With the increase of confining pressure, the peak stress and peak strain of rock salt will increase under the same temperature. Based on the test data, the Duncan-Chang constitutive model was modified, and the modified Duncan-Chang rock salt constitutive model considering the effect of temperature and confining pressure was established. The stress-strain curve calculated by the modified model was compared with the stress-strain curve obtained from the test. The close match between the test results and the model prediction suggests that the modified Duncan-Chang constitutive model is accurate in describing the behavior of rock slat under different confining pressure and temperature conditions.

Keywords: rock salt; triaxial compression test; temperature; confining pressure; mechanical properties; Duncan-Chang constitutive model

1. Introduction

Rock salt is considered as an ideal media for underground storage of energy such as oil and natural gas due to its excellent characteristics of low porosity, low permeability, strong plastic deformation capacity, and self-repair capacity (Li *et al.* 2012). The development and utilization of rock salt gas storage starts early, some research results on basic mechanical properties of rock salt were obtained (Khaledi *et al.* 2016, Hunsche and Albrecht 1990, Sheinin and Blokhin 2012, Böttcher *et al.* 2017, Chen *et al.* 2018). Along with the implementation of the "West-to-East Gas Transmission" project in China, the study of physical and mechanical properties of rock salt became one of the hot topics in rock mechanics in China. By using different test methods, some chinese scholars have carried out in-depth researches on the basic mechanical properties of rock salt, and the influence of various factors on the mechanical properties of rock salt were analyzed (Zhang *et al.* 2014, Li *et al.* 2014, Guo *et al.* 2014, Li *et al.* 2013). However, most of rock salt stores in 1,000 to 3,000m underground; and the underground temperature increases with the depth. For a burial depth of 3,000m, the temperature rises to about 90°C. Temperature exerts a great impact on the mechanical properties and deformation properties of rock salt (Moradi *et al.* 2018). Therefore, it is necessary to investigate mechanical properties of rock salt with consideration of temperature effect.

Mechanical properties of rock under the coupled effect of temperature and stress have always been an attractive research topic of scholars. By using the triaxial compression test, Morteza and Richard (2016) studied the mechanical properties of shale under the coupled action of high ground stress and high temperature. Wu *et al.* (2013) investigated physical and mechanical properties of sandstone at 1,200°C. Sriapai *et al.* (2012) conducted researches of the influence of temperature on the compressive and tensile strength of rock salt. Zhang *et al.* (2015) carried out triaxial compression tests on marble and sandstone under different temperatures and confining pressures, and compared the effect of confining pressures and temperatures on mechanical properties of the two types of rock. Rossi *et al.* (2018) conducted studies on the influence of high temperature and high heating rate on rock strength. All the above studies indicate that temperature will have a deteriorative effect on mechanical properties of rocks.

Rock constitutive model considering temperature effect is also an intensive research field in rock mechanics recently. Mahmoudi *et al.* (2016) developed a new triaxial experimental setup to study the characteristics of rock salt undergoing thermo-mechanical cyclic loading, and established an elasto-viscoplastic creep constitutive model considering dilatancy, damage progress and temperature effects. On the basis of statistical damage theory, Zhou *et al.* (2017) established a constitutive model under the coupled action of rock cyclic stress and temperature. Wang *et al.* (2018) carried out dynamic compression tests of granite at different temperatures and built a damage constitutive

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model of granite based on Weibull distribution. Xu and Xu (2017) established a statistical constitutive formula of rock damage under temperature effect by taking elastic modulus as the thermal damage variable and the rate change of the stress-strain curve of rock in different loading stages.

Even though many studies have been conducted on the mechanical properties of rock salt from different perspectives, with consideration of various types of rock under different temperatures, the investigation considering the influence of temperature on rock salt is rare. In addition, the research on the constitutive model considering the coupled action of temperature and confining pressure is seldom reported. This paper analyzes the influence of temperature and confining pressure on the mechanical properties of rock salt by using triaxial compression tests of rock salt at different temperatures. On the basis of collected test data, a revised Duncan-Chang constitutive model of rock salt considering temperature effect is established to serve as a reference for engineering design and construction of drilling through deep rock salt and rock salt gas storage.

2. Test overview

2.1 Specimen preparation

The rock salt specimen used in the test is the deep-buried rock salt found in the drilling of oil and gas wells in the western region of China. The color of the specimen is light yellow and the average density is about 2.17 g/cm^3. As shown in Fig. 1, the core is processed into a cylindrical solid standard specimen with a diameter of 50mm and a height of 100mm by using the indoor dry sawing method. The size of rock salt specimens shall be processed following the International Society for Rock Mechanics (ISRM) test procedures, with an allowable error range of ±0.3 mm in diameter and the non-parallelism of upper and lower end faces of ±0.05 mm. The wave speed of the processed standard rock specimen was measured, and rock specimens with similar wave speed were selected for the test. The wave speed of this batch of rock salt specimens is about 3.030 km/s. The processed rock salt specimens are numbered, wrapped with preservative film and stored in a dry sealed container. Dimension parameters and fundamental physical properties of the rock salt specimens are recorded and shown in Table 1.

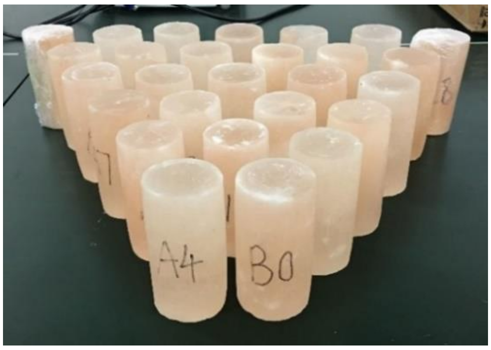


Fig. 1 Rock salt specimens

Table 1 Dimension parameters and physical properties of rock salt specimens

No.	Mass /g	Height /mm	Diameter /mm	Density /(g/cm^3)	Wave speed /(km/s)
1	423.67	100.14	50.03	2.15	3.030
2	436.39	100.17	50.25	2.20	3.030
3	411.38	99.86	49.75	2.12	3.125
4	422.89	99.99	50.17	2.14	3.030
5	432.10	100.17	50.29	2.17	3.030
6	439.40	99.96	50.12	2.23	3.030
7	434.77	99.87	50.07	2.21	2.941
8	432.14	100.19	50.14	2.19	2.941
9	416.22	99.79	49.88	2.14	3.030
10	429.62	100.16	50.12	2.18	2.941
11	423.87	100.17	50.09	2.15	2.941
12	420.16	100.25	50.12	2.13	3.030

2.2 Test equipment

As shown in Fig. 2, TFD-2000 triaxial rock rheometer is used in the test. The device is mainly composed of a shaft pressure system, a confining pressure system, a high-low temperature system and a pore water pressure system. The device can be used to carry out triaxial compression tests, triaxial rheological tests, pore penetration tests and high-low temperature environment tests under different confining pressure. The maximum axial force of the rheometer is 2,000 kN, the maximum confining pressure is 100MPa, and the maximum pore water pressure is 70MPa. The temperature could be controlled from room temperature to 200°C. In the test, the data is automatically collected by the microcomputer and analyzed in real time.

2.3 Test method

The processed standard rock salt specimen is put between the two rigid pads so that the specimen and the two pads are on the same axis. The three components are sealed with a heat shrinkable tube and the two ends are tightened with iron wire to prevent oil from entering. The circumferential extensometer is put in the middle of the specimen, while the axial extensometer is fixed on the upper and lower cushion blocks respectively. The instrumented specimen is seated onto the pressure chamber base, and the pressure chamber is sealed after checking. Then the oil pump is switched on to fill the pressure chamber with oil, and the oil temperature is heated to the set value such as 20°C, 40°C, 60°C, and 80°C at a speed of 2°C/min. The temperature is kept constant for 2 hours so as to heat the rock salt evenly. At a loading speed of 0.5 MPa/s, the specimen is loaded to a hydrostatic pressure state with the confining pressure at 1 MPa, 2 MPa and 3 MPa respectively, and then the axial load is applied using a displacement control mode of 0.2 mm/min until the rock salt is completely failed. It should be noted that the confining pressure values in the test are set as 1 MPa, 2 MPa and 3 MPa. However, the deformation generated during the triaxial test of higher confining pressure on rock

Fig. 2 TFD-2000 microcomputer servo control rock triaxial rheometer

salt has exceeded the measurement range of the axial extensometer, so the lower confining pressure is selected for the test to proceed smoothly. In addition, the change of confining pressure has a great influence on the deformation characteristics of rock salt, therefore the mechanical characteristics and deformation characteristics of rock salt under low confining pressure are also worth studying.

3. Test result and analysis

3.1 Stress-strain curve analysis

The axial deviatoric stress-strain curve of rock salt obtained at different temperatures in a triaxial compression test is shown in Fig. 3. From the figure, it can be seen that there is no initial compaction stage in the stress-strain curve of the rock salt, which reflects there are few pores and fractures in rock salt. The elastic stage of rock salt is also relatively short. With the increase in stress, it quickly enters the plastic deformation stage. At this stage, the stress-strain curve gradually flattens out and the plastic deformation is significant, especially with the increase in temperature. In the failure stage, the rock salt still reaches a high bearing capacity, different from conventional brittle rock whose bearing capacity will decrease suddenly. With the increase of confining pressure and temperature, the stress-strain curve becomes smoother after the peak stress.

From Fig. 3, it can also be seen that temperature has a great influence on the strength and deformation characteristics of rock salt. It mainly shows that under the same confining pressure, the peak stress of rock salt decreases obviously with the increase of temperature, and the plastic strain becomes more obvious with the increase of temperature. In addition, under the same deviatoric stress, the axial deformation of the rock salt increases obviously with the increase of temperature, which indicates that the increase of temperature will strengthen the strain softening property of the rock salt. The increase in temperature will cause thermal expansion of various mineral particles in the rock salt, while different mineral particles have different expansion coefficients, so it results in uncoordinated thermal expansion across particle boundaries. As a continuum, with the change of temperature, the mineral particles inside the rock salt will restrain each other due to

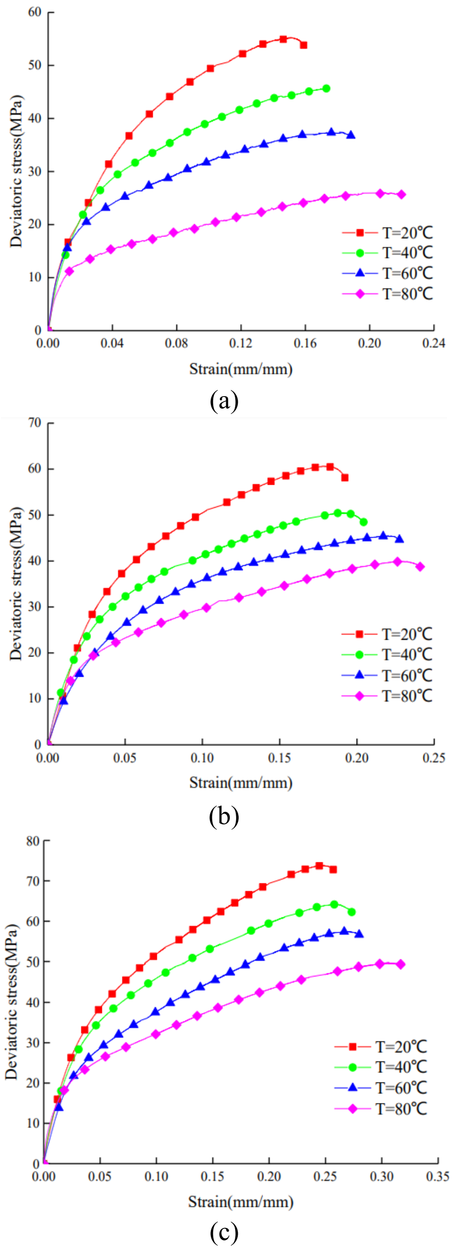


Fig. 3 Stress-strain curves of rock salt at different temperatures:(a) σ_3=1 MPa, (b) σ_3=2 MPa and (c) σ_3=3 MPa

different expansion coefficients, resulting in a thermal stress caused by temperature. When the thermal stress inside the rock reaches the strength limit of the rock, it will lead to cracking and produce microcracks at these locations, and it is possible that the microcracks will continue to spread into a network, which is the degradation of the mechanical properties of rock salt on the macro level (Li *et al.* 2013).

The statistics of test results of stress-strain curves at various temperatures and confining pressures is shown in Table 2. From the table, it can be seen that under the same temperature, the peak stress and peak strain of rock salt will increase with the increase of confining pressure. This is because that the lateral restraint of confining pressure on the rock salt, to a certain extent, limits the generation and expansion of internal cracks in the rock salt, which can

Table 2 Triaxial compression test results of rock salt at different temperatures

No.	Confining Pressure /MPa	Temperature /℃	Peak Stress /MPa	Peak Strain /(mm/mm)
1	1	20	56.31	0.15
2	1	40	46.69	0.17
3	1	60	38.59	0.18
4	1	80	27.49	0.20
5	2	20	62.76	0.18
6	2	40	52.53	0.19
7	2	60	47.45	0.22
8	2	80	41.99	0.23
9	3	20	77.06	0.25
10	3	40	67.24	0.26
11	3	60	60.45	0.27
12	3	80	52.83	0.31

improve the strength of the rock salt. Some scholars have also pointed out that under the high confining pressure, the triaxial compressive strength of salt rocks decreases with the increase of confining pressure, which is explained by the reason that the high confining pressure recombines the structure of the crystal particles of rock salt, and lattice dislocation causes micro-cracks among mineral particles, leading to the decrease instead of increase in the strength of salt rocks. (Guo *et al.* 2014).

3.2 Analysis of strength characteristics of rock salt

The change relationship between peak stress and confining pressure and temperature obtained from Table 2 is shown in Fig. 4.

From Fig. 4, it can be seen that the peak stress of rock salt is linearly related to confining pressure and temperature, respectively. Therefore, the peak stress can be expressed as a function of temperature and confining pressure through linear regression. The specific functional relationship is shown in Eq. (1) with a correlation coefficient of 0.979.

$$\sigma_1 = 50.61 - 0.40T + 11.06\sigma_3 \tag{1}$$

Meanwhile, the Mohr-Coulomb criterion expressed by principal stress can be indicated by the following formula (Wang and Lin 2018)

$$\sigma_1 = A\sigma_3 + B \tag{2}$$

wherein: $A = \frac{1+\sin\varphi}{1-\sin\varphi}$; $B = \frac{2c\cos\varphi}{1-\sin\varphi}$; c is the cohesion of rock; φ is the internal friction angle of rock.

The regression analysis of the data in Table 2 is carried out by using Eq. (2), parameters A and B can be obtained, and then cohesion c and internal friction angle φ can be determined by using the following formula

$$\varphi = \arcsin\frac{A-1}{A+1} \tag{3}$$

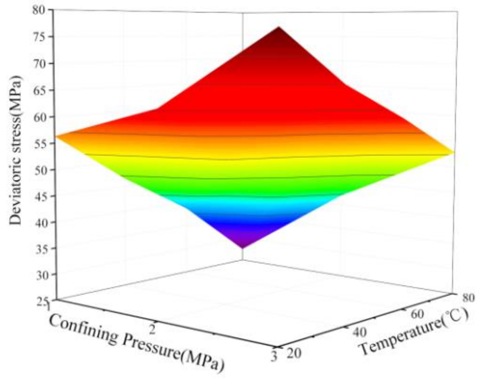


Fig. 4 Relationship between peak stress of rock salt and temperature and confining pressure

Table 3 Cohesion and internal friction angle of rock salt at different temperatures

Temperature/℃	Internal Friction Angle φ/°	Cohesion c/MPa
20	55.51	6.93
40	55.35	5.45
60	56.35	4.08
80	58.62	2.17

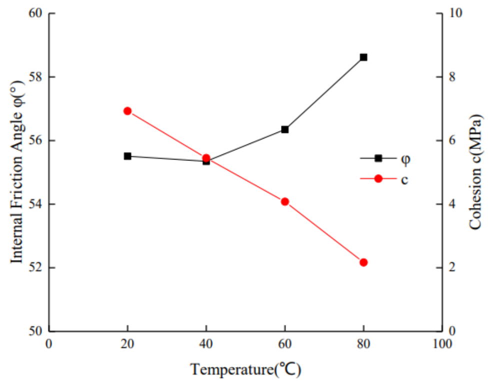


Fig. 5 Relationship between cohesion, internal friction angle and temperature of rock salt

$$c = \frac{B(1-\sin\varphi)}{2\cos\varphi} \tag{4}$$

Finally, values of c and φ obtained at different temperatures are shown in Table 3, and the relationship between temperature and c and φ is shown in Fig. 5.

As can be seen from Fig. 5, with the increase of temperature, the cohesion obviously decreases. The main reason is that the thermal stress caused by temperature causes microcracks between adjacent mineral particles, which reduces the interconnection force between particles and results in smaller cohesion of the rock salt. For the applied confining pressures, the internal friction angle slightly increases when the temperature rises from 20℃ to 80℃.

3.3 Failure mode

The failure mode of rock salt in triaxial compression test

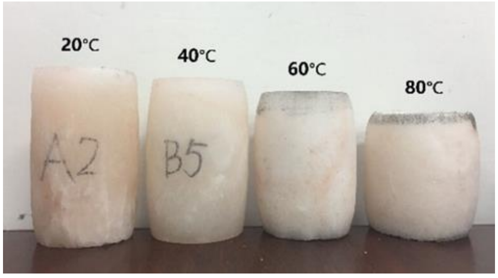


Fig. 6 The failure mode of rock salt under 3 MPa confining pressure

at different temperatures with a confining pressure of 3 MPa is shown in Fig. 6. It can be seen from the figure that in the triaxial compression test, the main failure mode of rock salt is axial splitting failure or expansion failure, and with the increase of temperature, the axial deformation and volume expansion of rock salt become more obvious. As can also be seen from Fig. 6, with the increase of temperature, the rock specimen gradually changes from yellow to white, mainly because that the large deformation causes a large number of friction, destruction and recombination of crystals in the rock salt, or that the temperature dehydrates certain minerals in the rock salt and leads to a change in color, which needs to be analyzed from a microscopic perspective in the future.

4. Duncan-Chang constitutive model considering temperature effect

4.1 Duncan-Chang constitutive model

In 1963, Kondner proposed for the first time to fit the triaxial stress-strain relationship of general soil with a hyperbolic curve according to the stress-strain curves of triaxial tests of a large number of soils (Mei *et al.* 2010). After that, Duncan and Chang (1970) proposed Duncan-Chang model according to the hyperbolic curve

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a + b\varepsilon_1} \tag{5}$$

wherein: $\sigma_1 - \sigma_3$ is the deviatoric stress; ε_1 is the axial strain; a and b are material parameters.

Later, since the Duncan-Chang model cannot describe the initial compaction stage and strain hardening stage of rock, Jiang *et al.* (2005) improved the model, and proposed a constitutive model of single rock that can describe the stress-strain relationship in the whole process of rock material failure, namely

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a + b\varepsilon_1 + c\varepsilon_1^2} \tag{6}$$

wherein: a, b and c are material parameters.

In Eq. (6), deformation characteristics of rock material in the initial compaction stage are considered and the strain softening of rock in the failure stage is described. Meanwhile, it can be found that Duncan-Chang model is simple with a few parameters which can be determined by test data. Therefore, Duncan-Chang model can be applied to the study of the rock salt constitutive model.

Table 4 Fitting results of parameter a, b and c of Duncan-Chang constitutive model

No.	σ_3 /MPa	T /°C	a	b	c	R^2
1	1	20	0.00058	0.016	-0.011	0.996
2	1	40	0.00050	0.020	-0.020	0.999
3	1	60	0.00045	0.031	-0.041	0.998
4	1	80	0.00053	0.056	-0.110	0.999
5	2	20	0.00077	0.011	0.007	0.993
6	2	40	0.00057	0.019	-0.014	0.998
7	2	60	0.00055	0.019	-0.007	0.998
8	2	80	0.00060	0.031	-0.037	0.996
9	3	20	0.00078	0.011	-0.001	0.998
10	3	40	0.00056	0.017	-0.015	0.998
11	3	60	0.00054	0.024	-0.032	0.995
12	3	80	0.00062	0.026	-0.027	0.996

4.2 Revised Duncan-Chang model of rock salt considering temperature effect

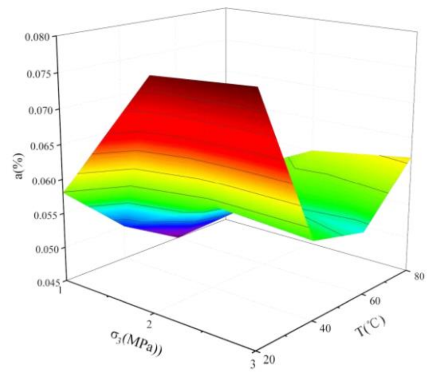
From the Duncan-Chang constitutive model mentioned above, it can be seen that the model only considers the influence of confining pressure on stress and strain, and fails to correctly reflect the influence of temperature and confining pressure on the strength and deformation characteristics of rock salt, and the parameters a, b and c are empirical values and have no reasonable physical significance.

Therefore, in the paper, Eq. (6) is revised and firstly the Eq. (6) is indicated as follows

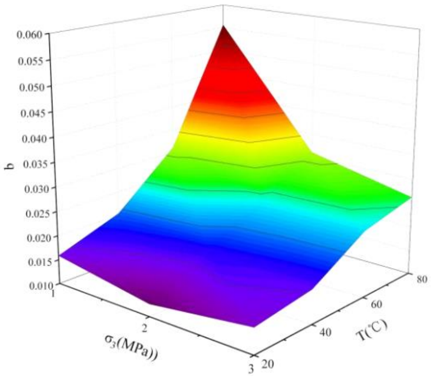
$$\frac{\varepsilon_1}{\sigma_1 - \sigma_3} = a + b\varepsilon_1 + c\varepsilon_1^2 \tag{7}$$

The triaxial compression test data of rock salt are analyzed according to Eq. (7), and test parameters a, b and c are obtained by fitting, as shown in Table 4.

The relationship between a, b and c and temperature and confining pressure is shown in Fig. 7, respectively. From Fig. 7 and Table 4, it can be concluded that: ① Parameter a first decreases and then increases with the increase of temperature, and increases and then stabilizes with the increase of confining pressure. ② With the increase of temperature and confining pressure, the parameter b shows monotonic increasing and monotonic decreasing trends, respectively. ③ Under the conditions of high temperature and low confining pressure, parameter c monotonically decreases and monotonically increases with the increase of temperature and confining pressure, respectively; under the conditions of low temperature and increased confining pressure, parameter c tends to be stable. Therefore, parameters a, b and c can be indicated by power functions of temperature and confining pressure.



(a)



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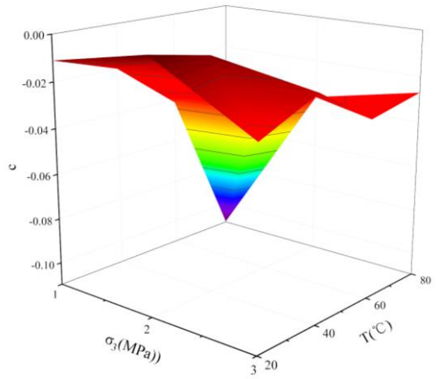
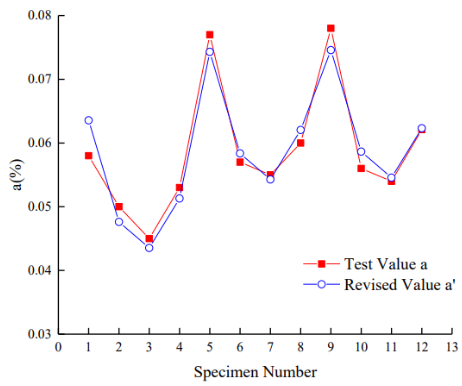
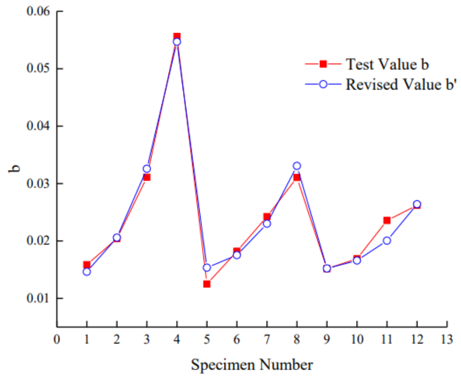


(c)

Fig. 7 Relationship between Parameters a, b, c and temperature, confining pressure: (a) *a*, (b) *b* and (c) *c*



(a)



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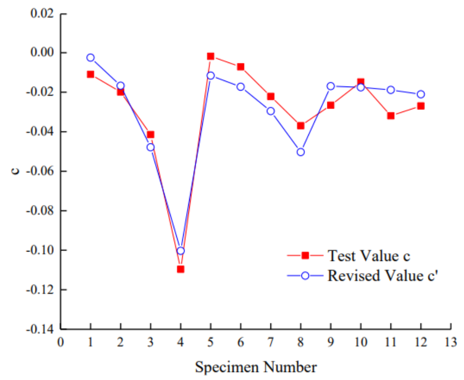


(c)

Fig. 8 Test value vs. revised value of Parameters a, b, c: (a) *a*, (b) *b* and (c) *c*

The parameters *a*, *b*, and *c* in Table 4 are revised by using the power function relation Eqs. (8)-(10) of temperature and confining pressure to obtain the revised parameters a', b' and c' respectively.

$$a' = 0.001 + 1.69\times10^{-5} T^{1.48\times10^{-7}} - 1.1\times10^{-4}\sigma_3^{-5.12} \tag{8}$$

$$b' = 0.015 + 1.65\times10^{-7}\sigma_3^{-1.135} T^{2.828} \tag{9}$$

$$\begin{aligned} c' &= 83.32 - 83.32\sigma_3^{-0.0002} - 0.0064T^{2.55} \\ &\quad + 0.0064\sigma_3^{-0.0002} T^{2.55} \end{aligned} \tag{10}$$

The revised parameters a', b' and c' reflect the influence of temperature and confining pressure on the rock, and the physical meaning is clearer. In order to verify the reliability of the revised parameters a', b' and c', the comparison of revised parameters a', b' and c' with the test values *a*, *b* and *c* is carried out, as shown in Fig. 8. It can be seen that the revised values and test values are consistent, and the fitting correlation coefficients obtained by using nonlinear fitting are 0.930, 0.958 and 0.871, respectively, which indicates that the revised parameters are reliable.

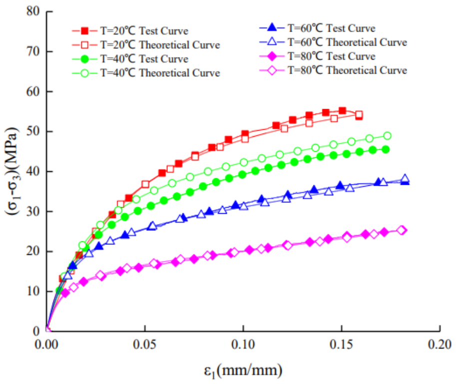
The revised Duncan-Chang constitutive model of rock salt considering temperature effect can be obtained by substituting the revised a', b' and c' into Eq. (6) as follows

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a' + b'\varepsilon_1 + c'\varepsilon_1^2} \tag{11}$$

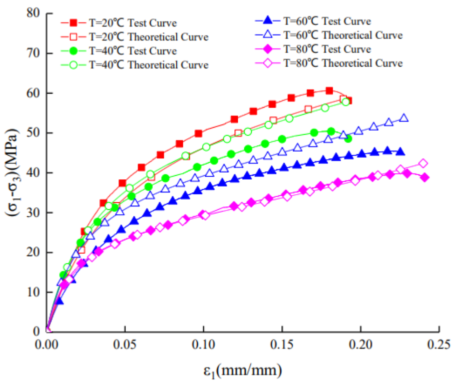
wherein $\sigma_1-\sigma_3$ is the deviatoric stress; ε_1 is the axial strain; a', b' and c' are functions of temperature and confining pressure, respectively, as shown in Eqs. (8)-(10).

4.3 Model verification

In order to further verify the rationality of the model and parameters, the comparison of the theoretical curve calculated by Eq. (11) with the test curve is carried out, as shown in Fig. 9. From the figure, it can be seen that the revised Duncan-Chang constitutive model can describe the stress-strain relationship curve relatively well, especially under 1MPa and 80°C, while the consistency under other conditions is relatively poor. However, on the whole, the method of considering temperature and confining pressure in Duncan-Chang constitutive model is applicable to a certain extent, and the modified Duncan-Chang constitutive model has certain rationality.



(a)



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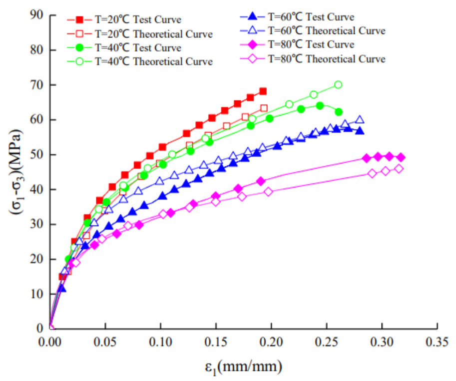

(c)

Fig. 9 Comparison of test curve and theoretical curve: (a) σ_3=1 MPa, (b) σ_3=2 MPa and (c) σ_3=3 MPa

5. Conclusions

Through the tests of rock salt under different confining pressures and temperatures, mechanical properties of rock salt have been characterized and fitted with the modified Duncan-Chang model. In summary,

- Temperature can exert degradation effect on the mechanical properties of rock salt, mainly as follows: with the increase of temperature, the peak strength of rock salt decreases obviously, and the plastic deformation characteristics become more and more obvious. The influence of confining pressure on the strength and deformation of rock salt is mainly shown as follows: with the confining pressure increasing, the peak stress and peak strain of rock salt will increase.
- Both temperature and confining pressure can affect the peak stress of rock salt. The relationship between peak stress of rock salt and temperature and confining pressure is obtained by using a linear regression following: σ_1=50.61-0.40T +11.06σ_3.
- Based on Mohr-Coulomb criterion, the c and φ values of rock salt at different temperatures are obtained and results show that the cohesion of rock salt decreases with the increase of temperature, while the internal friction angle slightly increases when the temperature rises from 20°C to 80°C.
- Under the action of temperature, the main failure mode of rock salt in triaxial compression test is axial splitting failure or expansion failure. The higher the temperature, the greater the final deformation is. With increase of temperature, the color of rock specimens gradually changes from light yellow to white.
- Based on Duncan-Chang model and regression analysis of the test data, a revised Duncan-Chang constitutive model of rock salt considering temperature effect is established. The constitutive model parameters a', b' and c' are figured out. By comparing the test data with the calculated values of the revised constitutive model, it is found that the results are closely matched.

Conflict of interest

The author declares that, with regard to the publication of this paper and the funding for publishing this paper, there is not any conflict of interest.

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