Rock Mech. Rock Engng. (2006) 39 (5), 469–482
DOI 10.1007/s00603-005-0067-2

Rock Mechanics and Rock Engineering
Printed in Austria

Experimental Study of Temperature Effects on Physical and Mechanical Characteristics of Salt Rock

By

W. G. Liang[1], **S. G. Xu**[1], and **Y. S. Zhao**[1,2]

[1] Mining Technology Institute, Taiyuan University of Technology, Taiyuan, P.R. China
[2] College of Energy Resource and Engineering, China University of Mining and Technology, Xuzhou, P.R. China

Received November 19, 2002; accepted May 17, 2005
Published online August 19, 2005

Summary

Because of its advantageous physical and mechanical characteristics, salt rock is considered an excellent host rock for nuclear waste disposal. Nuclear wastes in a salt rock repository will continue to emit radiation and thermal energy for decades after placement, resulting in a significant rise of the surrounding salt rock temperature. Consequently, study of the physical and mechanical characteristics of salt rock under different temperature conditions is essential to ensure the integrity of the salt rock repository and the safe isolation of nuclear wastes from the biosphere.

Through a series of physical and mechanical tests on thenardite salt rock at different temperatures (ranging from 20 °C to 240 °C), it is found that the mechanical parameters have different reactions to a changing temperature. Tests show that the ultrasonic velocity of samples decreases with temperature increase and both the uniaxial compressive strength and axial strain increase with temperature, whereas the tangent modulus E_t goes in an opposite direction. Meanwhile, the plastic strain increases gradually and strain-softening behavior of the samples becomes increasingly evident. In the pre-set angle shear tests, both the cohesion and internal friction angle increase with temperature. Results obtained in direct shear illustrate that both the peak shear strength and the ultimate shear strength increase with temperature.

We conclude that the behavior of thenardite salt rock at high temperatures is still advantageous to the integrity of salt rock repository, assuring the safe isolation of nuclear wastes from the biosphere.

Keywords: Salt rock, rock mechanics, temperature effect, physical and mechanical characteristics.

1. Introduction

Salt rock is found as large-scale deposits with simple structural and hydrologic conditions. Also, the overburden layers above typical salt rock deposits form a barrier between the salt and shallower ground water. The physical and mechanical characteristics of salt are evidenced in its compact texture, low porosity, low permeability and strong rheological properties (creep behavior). Consequently, salt rock is widely accepted as an ideal host for petroleum and natural gas storage caverns and can be also used to dispose of harmful and poisonous wastes, particularly radioactive nuclear wastes (Yang, 1989; Langer, 1993; Soppe et al., 1994; Cuevas et al., 1996; Staudtmeister and Rokahr, 1997; Kwon and Wilson, 1999).

After 40 years of operation of nuclear power plants, the proper disposal of radioactive nuclear wastes remains a critical and urgent problem (Soppe et al., 1993; Soppe and Prij, 1994). Disposing radioactive nuclear wastes in salt rock (rock salt) deposits has been widely accepted (Haupt, 1991; Sambeek et al., 1993; Chan et al., 1994, 1996, 1997; Chen, 1996; Doyle et al., 1997; Czerwinski et al., 1999; Renner et al., 2000; Mahnken and Kohlmeier, 2001), although many technical issues are still not fully resolved.

Soppe et al. (1994) indicate that nuclear wastes still have strong radioactivity after many years of underground disposal, leading to a long-term increase of the temperature in surrounding rocks. As a result, the temperature of the surrounding rocks of a 1000 m deep radioactive waste repository could reach as high as 165 °C. At high temperatures, the structure of the salt rock (rock salt) crystal and its physical and mechanical characteristics will change (Cuevas, 1997), therefore, to help understand long-term repository integrity, research on the changes of salt rock crystal structure and its physical and mechanical characteristics at high temperatures becomes important and necessary. In this paper, we discuss experimental results obtained from different tests on thenardite salt rock samples, including ultrasonic velocity tests and mechanical tests at different temperatures ranging from 20 °C to 240 °C.

2. General Information and Testing Procedures

All the thenardite salt rock samples tested were taken from a mirabilite deposit located 2200 meters underground at Hongze Lake (Jiangsu Province, China). The component of the samples is pure thenardite (Na_2SO_4). Samples of different shapes and sizes are tested according to ISRM suggested methods.

More than 20 groups of tests have been carried out in the laboratory at five different temperatures ranging from 20 °C to 240 °C. Ultrasonic velocity tests, uniaxial compression tests, pre-set angle shear tests and also direct shear tests were carried out. A SYC-2 sonic wave measuring instrument is used for the ultrasonic velocity tests. For compressive and shear strength tests, a WED-50 hydraulic pressure system is employed. Samples were heated to different temperatures with a HG101-3A electric heating box, with a maximum temperature of 300 °C.

All samples were prepared in accordance with ISRM suggested shape and size, and heated to different target temperatures for at least 12 hours. Then they were immediately tested in the various experimental configurations of the test program. To ensure the accuracy of the tests, at least three samples were tested in each group. As salt rock is a relatively soft rock, the loading rate is controlled to 0.5–0.7 MPa/s during the tests.

3. Ultrasonic Velocity Tests

Ultrasonic velocity tests are carried out with SYC-2 sonic wave measuring equipment. As shown in Fig. 1, with temperature increase the ultrasonic velocity of samples decreases from $3.17 \times 10^3\,\mathrm{m/s}$ at $20\,^\circ\mathrm{C}$ to $1.55 \times 10^3\,\mathrm{m/s}$ at $240\,^\circ\mathrm{C}$. The opposite trend for sample strength makes us presume that the internal structure of the salt rock has been changed during the heating process. The ultrasonic velocity of an ordinary rock also gradually decreases with the rising of temperature, but this decrease mainly arises from thermal cracking, i.e. spreading and increasing of internal fissures and voids, usually along crystal grain boundaries. However, direct shear tests for salt rock show that its cohesive strength increases with temperature (Section 6) as the texture of the crystallite becomes more compact and stronger, therefore the decrease of ultrasonic velocity of salt rock is different from that of ordinary rocks. This feature is undoubtedly advantageous to the stability of the salt rock repositories because higher temperatures actually leads to closure of microfissures and a more compact (lower permeability) structure. Through regression analysis, an exponential relation between ultrasonic velocity (V) and temperature (T) is obtained as

$$V = 3.38\,\mathrm{e}^{-0.0032\,T}[\times 10^3\,\mathrm{m/s}]. \tag{1}$$

4. Uniaxial Compression Tests

Three groups of uniaxial compression tests were carried out at temperatures of $20\,^\circ\mathrm{C}$, $120\,^\circ\mathrm{C}$ and $180\,^\circ\mathrm{C}$ respectively. Cylindrical specimens with diameter of 50 mm and height of 100 mm were tested. The results are shown in Table 1 and in Figs. 2–4.

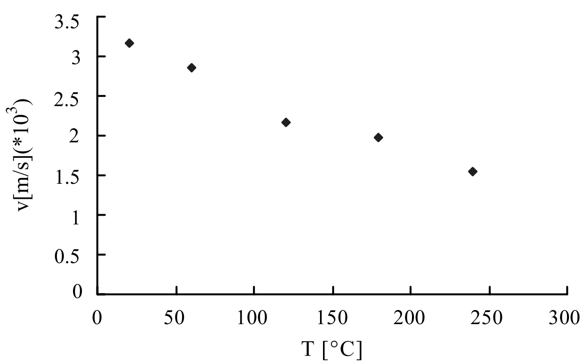


Fig. 1. The ultrasonic velocity changes of the salt rock with temperature increase from $20\,^\circ\mathrm{C}$ to $240\,^\circ\mathrm{C}$

Table 1. Results of uniaxial compression tests for salt rock at different temperatures*

Temperature [°C]	Peak load [KN]	Peak strength [MPa]	Tangent modulus [GPa]
20	20.8	10.6	2.15
120	36.3	18.5	1.87
180	40.6	20.7	1.14

* All theses values are average values from the three test groups.

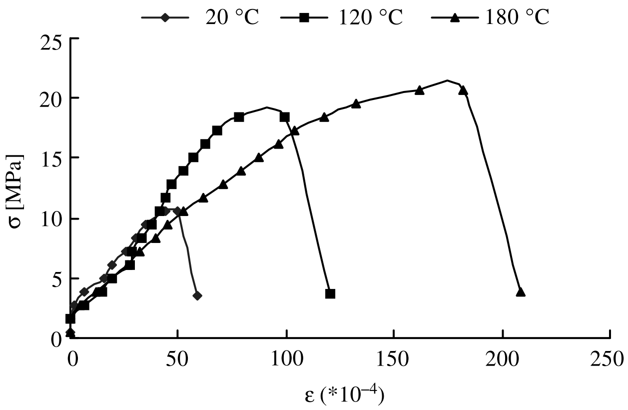


Fig. 2. Stress-strain curves of the salt rock during the uniaxial compression test at 20 °C, 120 °C, and 180 °C respectively

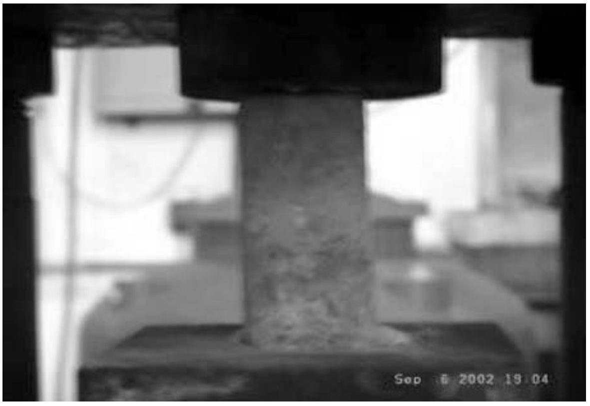


Fig. 3. Photo of cylindrical sample in unaxial compression test at 120 °C before failure

Fig. 4. Photo of cylindrical sample failure in unaxial compression test at 120 °C

It is found that the peak strength becomes greater as the temperature increases. Compared with the results at 20 °C, the peak strength at 180 °C increases by 95%, while the incremental ratio is 75% at 120 °C. These data are different from the results reported by Hunsche and Albrecht (1990) where they report that the strength of halite samples decreases significantly above 100 °C; our results indicate that the uniaxial compressive strength of salt rock is enhanced significantly with the rising of temperature, although the rate of strength increase decreases with rising temperature. From 20 °C to 120 °C, the strength increase rate is 0.08 MPa/°C, and 0.037 MPa/°C from 120 °C to 180 °C. With regression analysis, the relation between uniaxial compressive strength σ_c and the temperature T is deduced as

$$\sigma_c = 4.54 \ln(T) - 3.04 \text{ [MPa]}. \tag{2}$$

The axial strain of the salt rock is also measured during tests (Figs. 3, 4) and the stress-strain curves obtained are shown in Fig. 2. The deformation of salt rock can be described in four phases:

1) Small strain phase or "seating" phase, in which the axial stress increases from 0 to 2.5 MPa and the corresponding strain is nearly zero.

2) Elastic strain phase, in which the axial stress changes from 2.5 to about 10 MPa. This stress-strain behavior is defined as linearly elastic with an elastic modulus equal to 2.2 GPa.

3) Plastic strain phase, in which the axial stress changes from 10 MPa to the peak strength σ_c and the strain rate becomes obviously greater than that characterizing the former phases. Significant strains are observed during this phase.

4) Failure phase, in which the axial stress exceeds the peak strength σ_c and tensile spalling begins to occur on the free surface of the sample until it fails.

Compared with the stress-strain curve of ordinary rock samples, it is found that during the uniaxial compression tests salt rock does not have obvious fracture closure behavior because there are fewer pores and fissure voids in salt rock (the initial porosity is very low). This result agrees with that of Hunsche and Alberecht (1990) which shows that sample size has no influence on the measured strength. Meanwhile, the deformation during the plastic strain stage becomes more evident at high temperatures, which is consistent with other research results such as those reported by Kwon and Wilson (1999).

The stress-strain curves indicate that under uniaxial compression the physical and mechanical characteristics of salt rock change with temperature, and the failure mode of samples becomes more ductile. Both the compressive strength and the axial strain increase with temperature; at 120 °C the axial strain at failure is 1.55 times that at 20 °C, whereas at 180 °C it is 2.78 times that at 20 °C. However, it is found that the tangent modulus E_t decreases from 2.15 GPa at 20 °C to 1.14 GPa at 180 °C, which implies that the deformability of the salt rock is more pronounced with higher temperature.

It has also been found that under same loading, strain is greater with higher temperature. The peak strain at 180 °C reaches 182.35%, more than 3.7 times of that at 20 °C, which indicates that ductile strain softening behavior becomes greater with temperature.

5. Pre-set Angle Shear Tests

In a direct shear test, the angle between the shear plane and the horizontal plane is zero, while in the pre-set angle shear test this angle is pre-set as 40°, 45°, 50°, and 55° by using in each case a different container, i.e. the shear failure plane of each sample is pre-set. The peak failure stress is obtained in each test by giving the normal stress (σ) perpendicular to the shear plane, and the shear stress (τ) parallel to the same plane (Fig. 5).

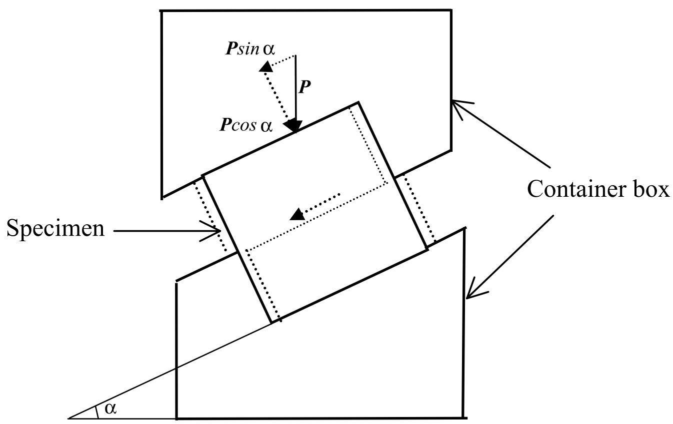


Fig. 5. Mechanical model of pre-set angle shear test, in which angle α between the shear plane and the horizontal plane can be changed with different container boxes. Different angles 40°, 45°, 50°, and 55° were used in the tests

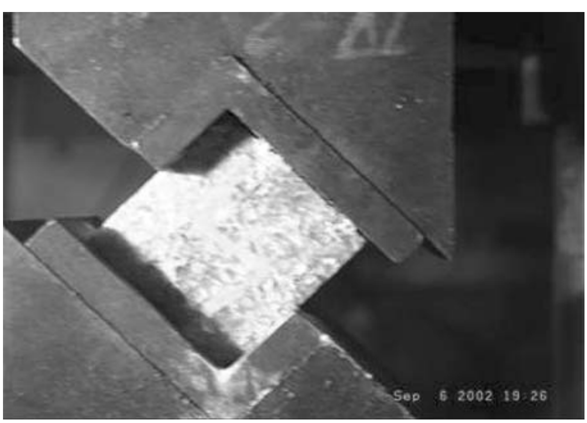


Fig. 6. Photo of cubic sample before failure in pre-set angle shear test with angle α of 60°

Fig. 7. Photo of the cubic sample in pre-set angle shear test with angle α of 60°

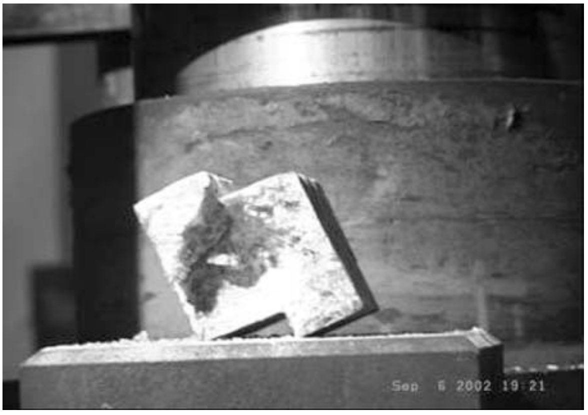


Fig. 8. Photo of failure sample of the salt rock in pre-set angle shear test at 120 °C with angle α of 40°

Table 2. Results of pre-set angle shear tests of salt rock at different temperatures*

Shear angle [°]	20 °C		60 °C		120 °C	
	σ [MPa]	τ [MPa]	σ [MPa]	τ [MPa]	σ [MPa]	τ [MPa]
40	13.95	11.71	20.34	17.07	34.44	28.9
45	10.31	10.31	16.75	16.75	27.3	27.3
50	8.61	10.26	10.72	12.77	12.34	14.7
55	5.68	8.11	7.5	10.71	9.37	13.38

* All theses values are average values from the three test groups.

Pre-set angle shear tests were carried out at three different temperatures: 20 °C, 60 °C, 120 °C (Figs. 6–8). Results are listed in Table 2 and in Figs. 9–11 by giving the failure envelopes for salt rock at different temperatures.

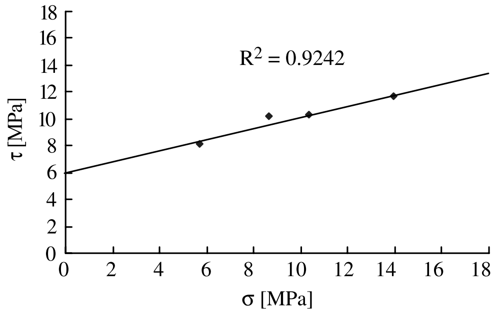


Fig. 9. The failure envelope obtained through regression analysis in the pre-set angle shear tests for the salt rock at 20 °C

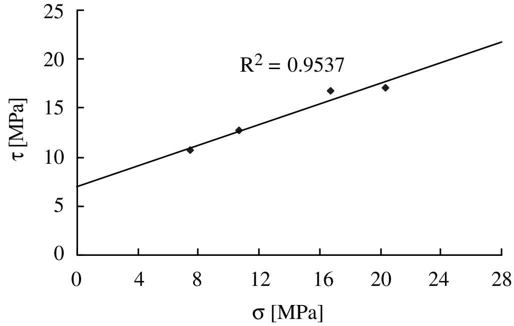


Fig. 10. The failure envelope obtained through regression analysis in the pre-set angle shear tests for the salt rock at 60 °C

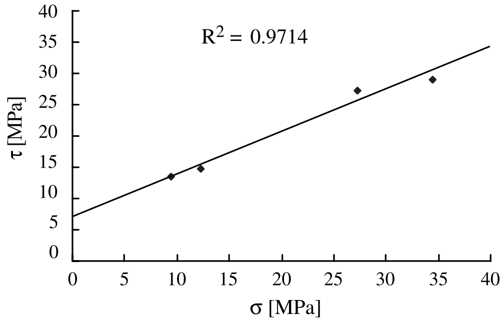


Fig. 11. The failure envelope obtained through regression analysis during the pre-set angle shear tests for the salt rock at 120 °C

Through regression analysis, the Mohr-Coulomb strength equations at temperatures of 20 °C, 60 °C, and 120 °C are obtained and shown below.

$$20\,^{\circ}\mathrm{C}: \tau = 6.11 + \sigma \tan 22.5^{\circ} \ [\mathrm{MPa}] \tag{3}$$

$$60\,^{\circ}\mathrm{C}: \tau = 7.06 + \sigma \tan 27.6^{\circ} \ [\mathrm{MPa}] \tag{4}$$

$$120\,^{\circ}\mathrm{C}: \tau = 7.09 + \sigma \tan 33.9^{\circ} \ [\mathrm{MPa}] \tag{5}$$

We note that both the cohesion and internal friction angle increase with temperature, with the increase of internal friction angle being more significant. This indicates that the shear resistance of salt rock increases with temperature, a result consistent with those from uniaxial compression tests.

6. Direct Shear Tests

Direct shear tests at five different temperatures ranging from 20 °C to 240 °C were carried out with a constant normal stress of 3 MPa. The test results are shown in Table 3 and Fig. 12(a)–(e).

As shown in Table 3, both the peak shear strength τ_{peak} and the ultimate shear strength τ_{ult} increase with temperature. At 240 °C, the peak shear strength τ_{peak} and the ultimate shear strength τ_{ult} are 9.3 MPa and 6.3 MPa respectively, both larger by approximately 30% of the value at 20 °C . With regression analysis, a relation between the peak shear strength (τ_{peak}) and temperature (T) is obtained as

$$\tau_{peak} = 0.0097\,T + 6.9609 \text{ [MPa]}. \tag{6}$$

Figure 12(a)–(e) indicates that the deformation can also be classified into four phases: linear elastic phase, plastic hardening phase, plastic softening phase and residual failure phase. It is found that with increasing temperature, the ductile deformation of rock salt becomes more evident during the second and third phase. The shear displacement increases with temperature. At 240 °C the shear displacement is 10 mm, almost 2.5 times of that at 20 °C. Figure 13 is the sample after failure in the direct shear test at 240 °C.

Additionally, it is found that during the tests the failure of salt rock at high temperatures is obviously different from that at normal temperatures, which is in accordance with the conclusions obtained previously. These data are in agreement with Hunsche and Albrecht (1990): at high temperatures samples exhibit ductile rather than brittle behavior. Meanwhile, acoustic emission occurs during the failure stage in the direct shear tests at 20 °C, but it becomes weaker with higher temperature.

Figure 14 shows a typical shear stress – shear displacement curve for sandstone at 240 °C. Different from the ductile behavior of salt rock, the sandstone specimen clearly exhibits brittle behavior during the tests. Furthermore, it is found that the ratio of the ultimate shear strength to the peak shear strength of salt rock is 60%, whereas for this sandstone it is 30%. Compared with sandstone, salt rock exhibits more typical soft rock behavior.

Table 3. Results of direct shear tests of salt rock at different temperatures*

Temperature [°C]	Sample appearance	τ_{peak} [MPa]	τ_{ult} [MPa]	Failure type
20	Yellow crystal	7.1	4.8	Brittle
60	Yellow crystal	7.5	4.8	Brittle
120	Shallow white	8.1	5.1	Ductile
180	Shallow white	8.7	5.4	Ductile
240	White	9.3	6.3	Ductile

* All theses values are average values from the three test groups.

7. Test Results Application Potentials in Salt Rock Repositories

Since the 1950s, salt rock has been widely accepted as an excellent host rock for the storage of natural gas and oil as well as for disposal of poisonous and hazardous wastes because of its advantageous physical and mechanical characteristics. Several salt rock repositories have been constructed, such as the intermediate-level radioactive waste repository at Olkiluoto, Finland, which is located 125 m underground, and the German

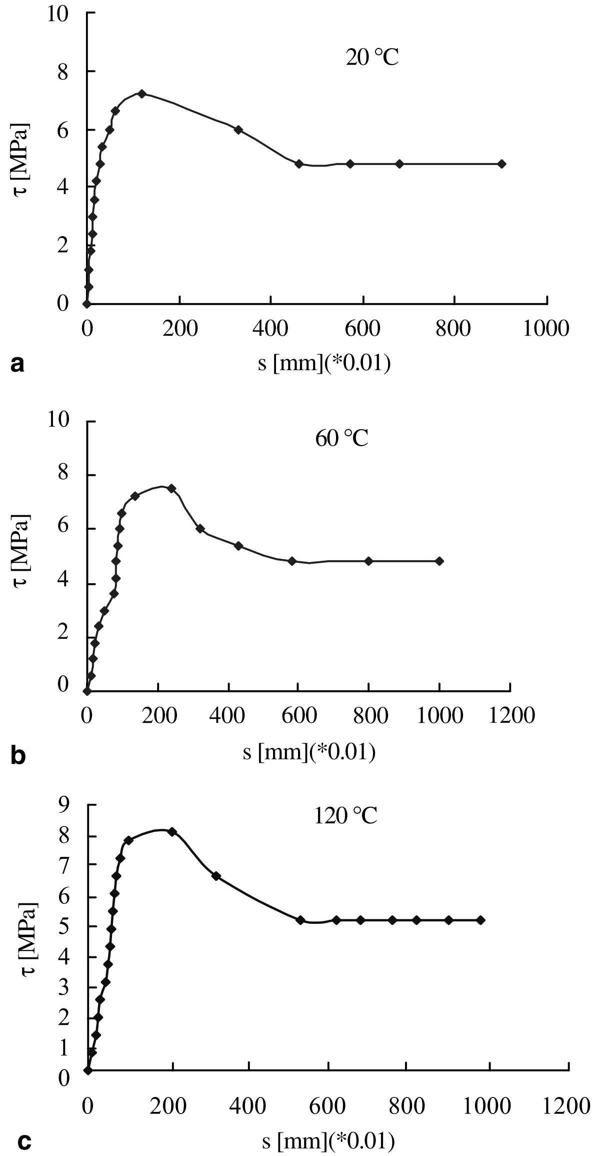
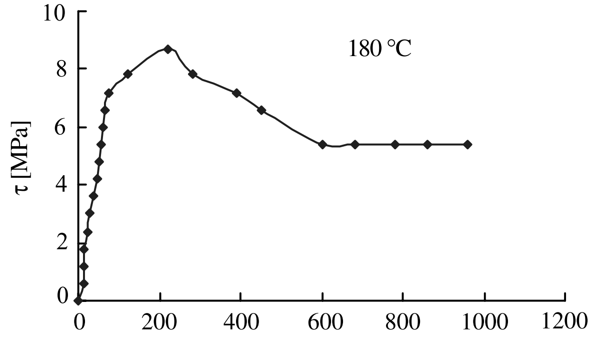
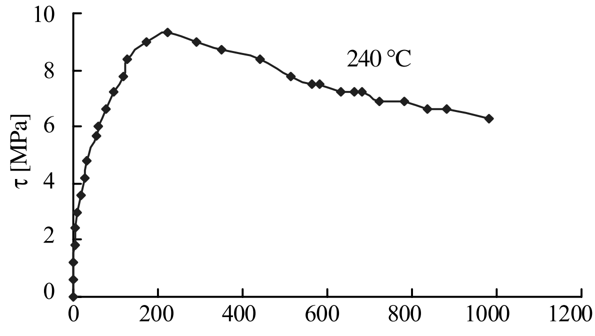


Fig. 12a–e. Shear stress versus shear displacement of the salt rock in direct shear test. **a**: at 20 °C; **b**: at 60 °C; **c**: at 120 °C; **d**: at 180 °C; **e**: at 240 °C



d



e

Fig. 12a–e (*continued*)

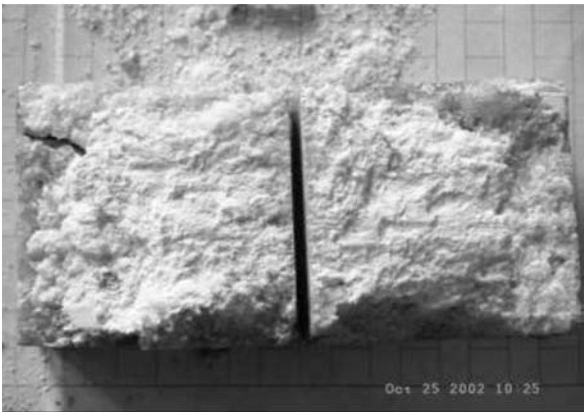


Fig. 13. Photo of the failed salt rock sample in direct shear test at 240 °C, the color of the failure face is white

repository near Morsleben which is located in an abandoned salt mine. Also to be noted is the Waste Isolation Pilot Plant (WIPP), an underground facility in bedded rock salt approximately 658 m below surface in a semi-arid region near Carlsbad, New Mexico,

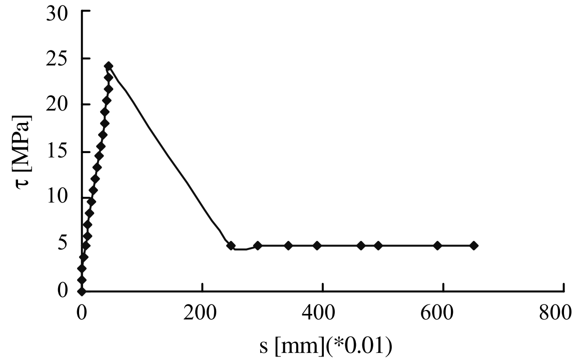


Fig. 14. Shear stress versus shear displacement of sandstone at 240 °C in direct shear test

U.S., which is fully operational and has been used for decades for weapons-based transuranics. It is the deepest repository ever designed in the world to store and isolate transuranic (TRU) waste (Committee on the Waste Isolation Pilot Plant, 1996).

The interaction of a repository with the biosphere is possible if there are connecting pathways such as fissures or fractures in the rock mass surrounding it. As time elapses, an originally well-sealed repository and the surrounding rock mass could undergo changes in its integrity to some extent, and some fissures and fractures might develop because of heating due to nuclear radiation, stress changes, and induced liquid flow. However, the ductile and "flowing" behavior of thenardite salt rock at high temperatures, as illustrated by the test results described above, is a great aid to maintaining the sealing characteristics of a waste repository, and in such rock, wastes can be encapsulated and isolated from the outside environment quickly and permanently. Furthermore, the enhanced strength and lower porosity of salt rock with time and temperature increase provide an additional security against breaching of the repository. Thus, neither waste outflow nor ground water inflow appears to be possible events, and the wastes can be assumed to remain in permanence with exceedingly low risks of biosphere interaction.

8. Conclusions

A series of tests on the physical and mechanical characteristics of thenardite salt rock at different temperatures (ranging from 20 °C to 240 °C) has shown that with increasing temperature, changes occur inside the salt rock crystallite, and several clear trends have been noted. As temperature increases, the ultrasonic velocity of the salt rock decreases, but both the uniaxial compressive strength and the shear strength are enhanced. These effects are summarized as follows.

The ultrasonic velocity test results show that the ultrasonic velocity decreases with increasing temperature, which indicates that the internal structure of the salt rock changes. Results of strength tests confirm that the change in behavior is different from the thermal cracking of ordinary rocks, and temperature causes the salt rock cohesive strength to increase, not decrease. It is observed that the ultrasonic velocity (V) and the temperature (T) of salt rock are exponentially related by $V = 3.38\,e^{-0.0032\,T}$ $[\times 10^3\,\mathrm{m/s}]$.

Uniaxial compression tests show that the strength of salt rock is enhanced with rising temperature. Compared with the strength at 20 °C, it increases 74.5% at 120 °C and 95.3% at 180 °C. The relationship between the uniaxial compressive strength (σ_c) and the temperature (T) of the salt rock is $\sigma_c = 4.54 \ln(T) - 3.04$ [MPa].

Uniaxial compression tests indicate that the stress-strain curve of salt rock differs from that of ordinary rocks because there is no early fracture closure stage and the flowing characteristics (ductility) are more evident at high temperatures. Moreover, the axial strain of the samples increases with temperature and the tangent modulus E_t decreases from 2.15 GPa at 20 °C to 1.14 GPa at 180 °C. At the same time, it is found that under the same load the deformation of the salt rock increases with temperature, indicative of the flowing characteristic of salt rock at high temperatures.

The Mohr-Coulomb envelopes for salt rock are obtained from pre-set angle shear tests at 20 °C, 60 °C, and 120 °C. Both the cohesion and the internal friction angle of salt rock increase with temperature.

In direct shear tests, both the peak shear strength and the ultimate shear strength increase with temperature. The relation of the peak shear strength (τ_{peak}) of salt rock versus temperature (T) is $\tau_{peak} = 0.0097\,T + 6.9609$ [MPa]. The failures mode of salt rock at high temperatures is more ductile than at low temperatures. Furthermore, the ratio of the ultimate shear strength to peak shear strength of salt rock is about twice as that of sandstone.

The physical and mechanical characteristics of thenardite salt rock at high temperatures demonstrate that its isolating effects are improved, which tends to reduce risk of nuclear wastes or fluids interacting with the biosphere, thus ensuring the safety of salt rock repositories. More research is needed to study the physical and mechanical characteristics of salt rock at high temperatures and careful consideration of these effects should be taken in the design of salt rock repositories.

List of Symbols

E_t	tangent modulus, GPa;
S	shear displacement, mm;
T	temperature, °C;
V	velocity, m/s;
σ	normal stress, MPa;
σ_c	uniaxial compressive strength, MPa;
τ	shear stress, MPa;
τ_{peak}	peak shear strength, MPa;
τ_{ult}	ultimate shear strength, MPa;
ε	strain.

Acknowledgments

This research has been supported by the National Natural Science Foundation of China (No. 50174040, 50304011, 50434050) and National Outstanding Youth Science Foundation of China (No. 59625409). Special acknowledgments should also be given to Professor Maurice B. Dusseault, who helped to revise the paper.

References

Cuevas, C. L. (1997): Pore structure characterization in rock salt. Engng. Geol. 47(1–2), 17–30.

Cuevas, C. L., Miralles, L., Pukyo, J. J. (1996): The effect of geological parameters on radiation damage in rock salt: Application to rock salt repositories. Nuclear Technol. 114, 325–336.

Chan, K. S., Bodner, S. R., Fossum, A. F., Munson, D. E. (1997): A damage mechanics treatment of creep failure in rock salt. Int. J. Damage Mech. 6(1), 122–152.

Chan, K. S., Brodsky, N. S., Fossum, A. F., Bodner, S. R., Munson, D. E. (1994): Damage-induced nonassociated inelastic flow in rock salt. Int. J. Plasticity 10(6), 623–642.

Chan, K. S., Munson, D. E., Bodner, S. R., Fossum, A. F. (1996): Cleavage and creep fracture of rock salt. Acta Mater. 44(9), 3553–3565.

Chen, Z., Wang, M. L., Lu, T., Zhou, S. J. (1996): A micro- and macro-mechanical investigation of creep mechanisms for the WIPP rock salt. Radioactive Waste Management and Environmental Restoration 20, 73–91.

Committee on the Waste Isolation Pilot Plant, Board on Radioactive Waste Management, Commission on Geosciences Environment and Resources, National Research Council (1996): The waste isolation pilot plant: A potential solution for the disposal of transuranic waste. National Academy Press, Washington, DC, 7–14.

Czerwinski, K. R., Draye, M., Faver, A., Foos, J., Guy, A., Lemaire, M. (1999): Ion selective resins: Development and applications for nuclear waste management. Mat. Res. Soc. Symp. Proc. 556, 1277–1284.

Doyle, G. A., Keith, D. C., Runnells, D. D., Tilk, J. (1997): Geochemistry of abandoned fluids associated with the proposed underground solution-mining project at white pine mine. Min. Engng. 4, 62–67.

Haupt, M. (1991): A constitutive law for rock salt based on creep and relaxation tests. Rock Mech. Rock Engng. 24, 179–206.

Hunsche, U., Albrecht, H. (1990): Result of true triaxial strength tests on rock salt. Engng. Fract. Mech. 35(4/5), 867–877.

Kwon, S., Wilson, J. W. (1999): Deformation mechanism of the underground excavations at the WIPP site. Rock Mech. Rock Engng. 32(2), 101–122.

Langer, M. (1993): Use of solution-mined caverns in salt for oil and gas storage and toxic waste disposal in Germany. Engng. Geol. 35(3–4), 183–190.

Mahnken, R., Kohlmeier, M. (2001): Finite element simulation for rock salt with dilatancy boundary coupled to fluid permeation. Computer Methods Appl. Mech. Engng. 190, 4259–4278.

Renner, J., Hettkamp, T., Rummel, F. (2000): Rock mechanical characterization of an argillaceous host rock of a potential radioactive waste repository. Rock Mech. Rock Engng. 33(3), 153–178.

Sambeek, L. V., Ratigan, J., Hansen, F. D. (1993): Dilatancy of rock salt in laboratory tests. Int. J. Rock Mech. Sci. Geomech. Abstr. 30, 735–738.

Soppe, W. J., Donker, H., Garcia, C. A., Prij, J. (1994): Radiation-induced stored energy in rock salt. J. Nuclear Mater. 217(1–2), 1–31.

Soppe, W. J., Prij, J. (1993): Radiation damage in a rock salt nuclear waste repository. Nuclear Technol. 107, 243–253.

Staudtmeister, K., Rokahr, R. B. (1997): Rock mechanical design of storage caverns for natural gas in rock salt mass. Int. J. Rock Mech. Min. Sci. 34(3/4), 646.

Yang, J. G. (1989): Discussion on prospect of nuclear waste disposal in rock salt in China. J. Huadong Geology College 12(2), 55–62.

Author's address: Dr. Weiguo Liang, Mining Technology Institute, Taiyuan University of Technology, Taiyuan, 030024, China; e-mail: master_lwg@hotmail.com