Thermomechanical Behaviour of Rock Salt

Sasan Moravej
School of Civil Engineering, The University of Queensland, St Lucia, Brisbane, Australia

Mehdi Serati
School of Civil Engineering, The University of Queensland, St Lucia, Brisbane, Australia

Mojtaba Bahaaddini
School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran

David John Williams
School of Civil Engineering, The University of Queensland, St Lucia, Brisbane, Australia

ABSTRACT: The stability and integrity of salt caverns are critical for ensuring their safety and long-term viability, especially when used for storing hydrogen on large scales. This study is aimed at understanding the failure mechanisms of rock salt under coupled thermo-mechanical stress regimes based on the study of rock salt dilatancy-compression boundary stress levels. Several tests were conducted using a high-temperature true triaxial testing facility on 50 mm high-purity rock salt cubes. Different temperatures of 30 °C and 100 °C were considered, along with a variety of stress values of 0, 5, 10, and 20 MPa for confining pressures. The results showed that the applied deviatoric stress and temperature both have significant coupling impacts on the peak strength and dilatancy boundary of rock salt.

Keywords: Salt cavern, Dilatancy boundary, peak strength, intermediate principal stress, high temperature.

1 INTRODUCTION

This Hydrogen is a promising solution, in response to the increasing demand for sustainable and low-emission energy sources in Australia and worldwide. However, due to its highly flammable nature, safe and effective storage methods with large capacities are necessary. One potential option is to store hydrogen underground in salt caverns, which has been proposed as one of the most viable options for large-scale storage. Rock salt caverns are ideal for the storage of hydrogen, oil, natural gas, petroleum products and other hydrocarbons, compressed air, carbon dioxide, and chemical and hazardous waste disposal due to their impermeability, and structural stability (Djizanne et al., 2014). They are usually constructed deep underground, typically between 1,500 and 2,500 meters, and can reach high temperatures of up to 90 °C due to geothermal gradients. Because of the associated high geological stresses and high temperatures involved, constructing and operating these caverns is challenging, making accurate design crucial.

The complete stress-strain curve of rock salt consists of several stages, including compaction, elasticity, plasticity, and failure as shown in Figure 1a. Under loading, there is the stress level at which cracks cause permanent damage called dilatancy boundary. It signifies the end of stable crack growth and the beginning of a transition from compaction to dilatancy, leading to an increase in pore volume and significantly higher permeability. Dilatancy in rock salt is equivalent to the crack damage threshold of brittle materials. The volumetric strain graph, illustrated in Figure 1, is a reliable indicator of dilatancy (Stormont, 1997; Schulze et al., 2001; DeVries et al., 2002; Serati et al., 2016, Serati et al., 2018).

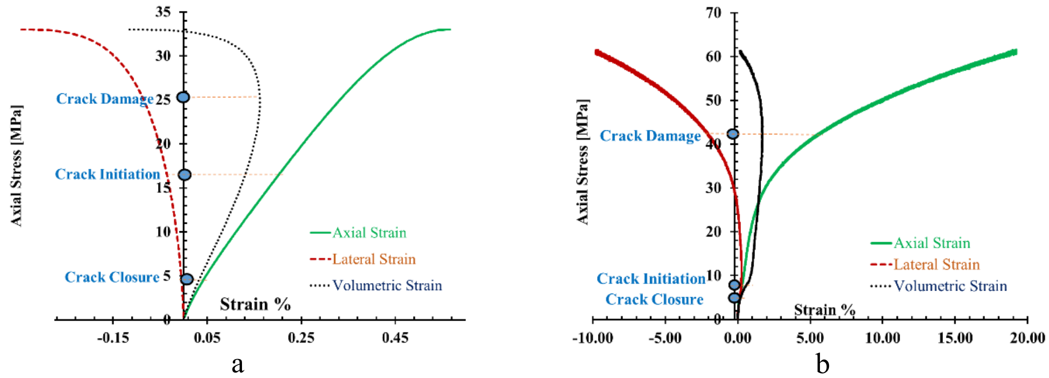

Figure 1. (a) crack damage in brittle material (b) dilatancy boundary in rock salt.

Accurate prediction of dilatancy is crucial to validate the effectiveness of closure and sealing constructions, as well as to ensure the hydraulic tightness of geological barriers surrounding openings (Labaune et al., 2018; Liu et al., 2020). In recent years, dilatancy has emerged as a widely accepted standard for designing underground structures situated in salt formations as it can significantly impact their stability and integrity. Several stress-based criteria have been developed based on the dilatancy phenomenon to ensure safe and stable salt cavern design (Van Sambeek et al. 1993; Spiers et al. 1989; Hunsche 1993; Hou 2003; DeVries et al. 2005).

Various factors affect rock salt dilatancy and its measurement, including specimen variability, geometry, material heterogeneity, preconditioning, loading conditions, and measurement techniques (DeVries and Mellegard, 2010; Medina-Cetina and Rechenmacher, 2010; Lüdeling et al., 2015). Experimental studies investigating the effect of loading conditions on dilatancy have mainly focused on the effects of confining pressure and minimum principal stress, with intermediate σ_2 stress often overlooked for simplicity (Hou, 2003; DeVries et al., 2005; Rouabhi et al., 2019). However, in-situ stress measurements have revealed that rocks often experience anisotropic stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$), and intermediate σ_2 stress can be critical to rock failure (Serati et al., 2022, Moravej et al., 2023). In this study, we investigate the thermomechanical behaviour of rock salt in dilatancy and consider the effect of σ_2 stress. Our analysis aims to provide a more comprehensive understanding of the complex relationship between stress and dilatancy in rock salt.

2 EXPERIMENTAL TESTING

For the purpose of testing, we selected high-purity salt specimens (98% NaCl) from the Khewra Salt Mine in Pakistan. These specimens had a compact structure and were pink and transparent in appearance. The tests were performed using a multi-functional true triaxial testing facility available in the Geotechnical Engineering Centre (GEC) at the University of Queensland. The machine can conduct three-dimensional loading and thermo-mechanical testing on rock samples (see Figure 2). Rock salt samples for testing were cut into 50 mm cubes and then ground to make sure the surfaces were smooth. The samples were tested under true triaxial loading conditions, where $\sigma_1 \geq \sigma_2 \geq \sigma_3$, at two different temperatures: room temperature (30 °C) and 100 °C. Please refer to Table 1 for details of the test program.

To prevent the formation of potential cracks due to thermal effects, a low incremental rate of 2 °C/min was maintained during heating from room temperature up to 100 °C for the samples group under high temperature. The specimens were first subjected to an initial seating load of 5 KN in all three directions of σ_1, σ_2, and σ_3 to prevent them from becoming off-centre during the test.

Subsequently, loads were applied at a rate of 15 kN/min (or 0.1 MPa/s), with stresses increasing simultaneously from the seating load of 5 KN to the designated σ_2 and σ_3 stresses according to the testing plan. This process was carried out at both room temperature and 100 °C.

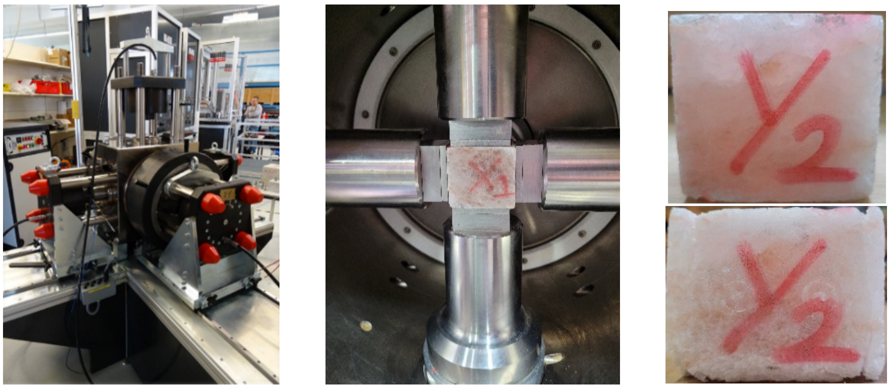

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Figure 2. The Test configuration setup: (a) True triaxial system at UQ Geotechnical Engineering Centre, (b) sample positioned inside the true triaxial cell, and (c) sample before and after test.

Table 1. Testing parameters.

Polyaxial Stress State	**Temperature (°C)**	**σ_3 (MPa)**	**σ_2 (MPa)**
	30	0	0
	100	5	5
$\sigma_1 \geq \sigma_2 \geq \sigma_3$	-	10	10
	-	20	20
	-	-	30

3 TEST RESULT

Rock salt is renowned for its high strength and significant deformability under triaxial compression conditions due to a phenomenon known as "strain hardening." Consequently, determining the peak strength is challenging since it does not fracture even at axial strains of 20–30%. In previous studies, researchers found the peak strength by employing the major principal stress at specific axial strains. However, there is no consensus on the axial strain at which the peak strength should be identified, with suggested values ranging from 4% to 15% under low-temperature conditions (Liu et al. 2006; Liu et al. 2014a, b; Ma et al. 2012; Li 2015; and Liu et al. 2020). However, as the temperature increases, the axial strain increases considerably, necessitating a higher axial strain threshold. In this study, we used an axial strain of 20% as the peak strength of rock salt. While using such a high axial strain has no practical significance, we employed it to compare the two sample sets at room temperature and 100 °C (Liu et al., 2011, Ye et al., 2022). Figure 3 displays the peak strengths for different values of σ_2 with σ_3 at temperatures of 30 °C and 100 °C. The figure illustrates that increasing the temperature from 30 °C to 100 °C significantly reduces the peak stress for all minor principal stresses.

The UCS and biaxial test results differ significantly from the triaxial test results for rock salt. At low or zero confining pressures, rock salt exhibits strain-softening and brittleness properties. Increasing confining pressures result in an increase in the elastic portion of the stress-strain curve, as well as the axial strain associated with peak stress.

When σ_3 surpasses a specific value called Transition Confining Pressure (TCP) threshold, rock salt failure shifts from brittleness to ductility, as demonstrated by many previous triaxial compression tests (Liu et al. 2006; Liang et al. 2007; Li et al. 2014). Under such a condition, rock salt displays significant deformability, high strength, and excellent plasticity. These properties make it an ideal environment for gas storage in salt caverns, ensuring necessary stability and tightness (Ma et al., 2017).

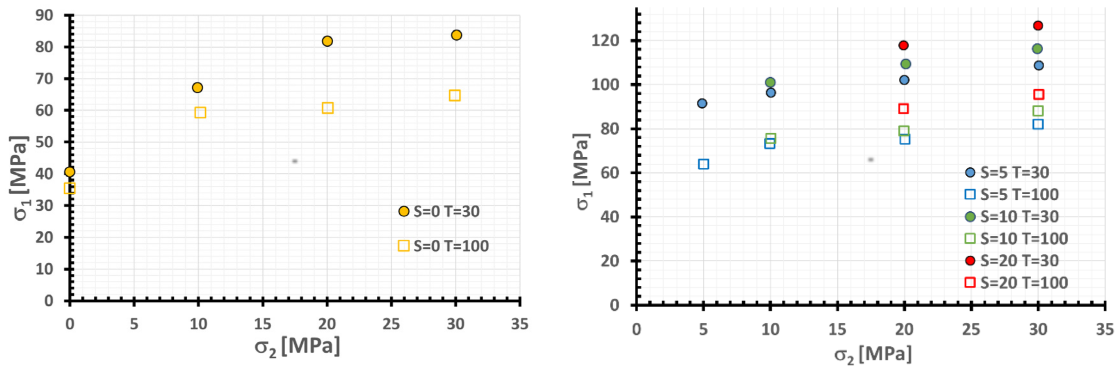

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Figure 3. The peak strength of rock salt under (a) UCS and biaxial conditions (b) triaxial and true triaxial conditions (T: Temperature; S: σ_3).

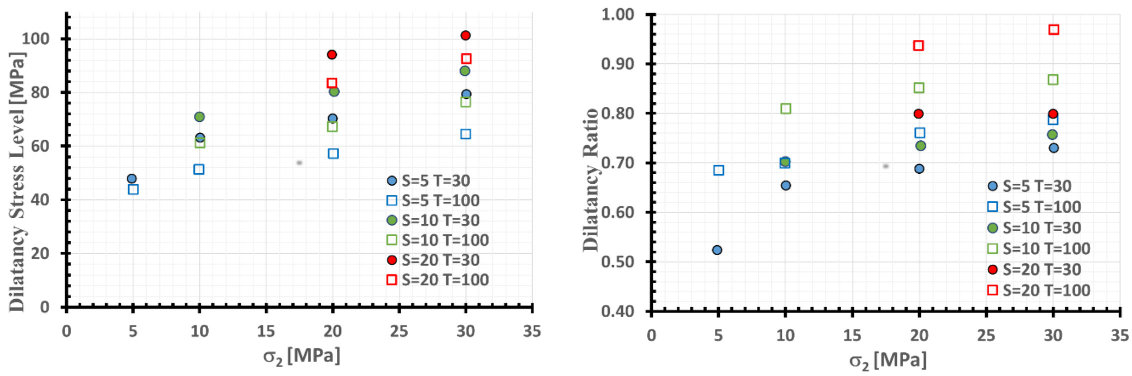

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Figure 4. (a) Dilatancy stress level (b) Dilatancy to peak strength ratio of rock salt under different conditions (T: Temperature; S: σ_3).

The dilatancy boundary values obtained from the volumetric strain graph, for all the tests, have been shown in Figure 4a. It is observed that an increase in σ_2 and σ_3 leads to an increased dilatancy boundary. However, an increase in temperature results in dilatancy occurring at lower stress levels. In addition, under the same σ_2, a rise in minor principal stress reduces the temperature-induced deterioration effect.

To analyze the stress data, we examined the ratio of dilatancy boundary stress to peak strength (referred to as the Dilatancy ratio), as shown in Figure 4b. It is evident that as the minor principal stress increases, the dilatancy ratio significantly rises for both thermal groups. This observation suggests a transition from brittleness to ductility as σ3 increases. Notably, a sharp increase occurs at σ_3 values between 5 and 10 MPa, indicating that TCP falls within this range. Conversely, σ_2 does not exert the same influence on the dilatancy ratio. When the minor principal stress is high, the intermediate principal stress has minimal impact on the dilatancy ratio. Moreover, at elevated temperatures, these ratios are significantly higher compared to those observed at ambient temperatures.

We employed the derived dilatancy stress levels of rock salt to identify stress points for both normal mean stress and octahedral shear stress. These stress points were plotted in the (σ_m - σ_{oct}) plane to demonstrate the compressibility-dilatancy boundary curve, as presented in Figure 5. It is obvious that temperature has significant effects on the compressibility-dilatancy boundary of rock salt.

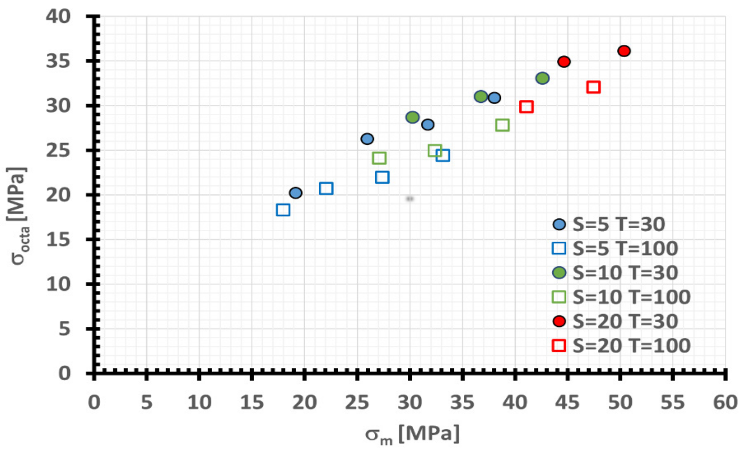

Figure 5. Dilatancy boundary of the rock salt in the (σ_m - σ_{oct}) plane (T: Temperature; S: σ_3).

4 CONCLUSION

Designing salt caverns to store hydrogen, compressed air, and carbon dioxide storage requires considering dilatancy, a critical factor that can affect their stability and integrity. While some studies have explored the thermo-mechanical behavior of rock salt, the combined effect of high stresses and temperatures on dilatancy remains poorly understood. To address this gap, our study investigates the thermomechanical behavior of rock salt in dilatancy, focusing on the effect of σ_2 stress. We conducted true triaxial loading tests on rock salt samples at two different temperatures, 30 °C and 100 °C. Our findings reveal that an increase in temperature results in a decrease in peak strength and dilatancy, while an increase in σ_2 and σ_3 increases both. We also discovered that a rise in minor principal stress reduces the temperature-induced effect, especially at higher intermediate principal stresses. It is worth noting that when σ_2 is closer to σ_3, it is more effective in mitigating the adverse effects of temperature. Furthermore, at high temperatures, the dilatancy ratios to peak strength are considerably higher than those observed at ambient temperatures, owing to high axial strains. By improving the understanding of the combined effect of high stresses and temperatures on dilatancy in salt caverns, our study can inform the more accurate and reliable design of these crucial energy storage facilities.

REFERENCES

DeVries, K. L., & Mellegard, K. D. (2010). Effect of specimen preconditioning on salt dilation onset. In SMRI Fall 2010 Technical Conference. Leipzig, Germany; October 2010.

DeVries, K. L., Mellegard, K. D., & Callahan, G. D. (2002). Salt damage criterion proof-of-concept research. Technical Report, RESPEC, Rapid City, South Dakota.

DeVries, K. L., Mellegard, K. D., Callahan, G. D., & Goodman, W. M. (2005). Cavern roof stability for natural gas storage in bedded salt. Technical Report DE-FG26-02NT41651, RESPEC, Rapid City, South Dakota.

DeVries, K., Callahan, G., & Mellegard, K. (2005). Numerical simulations of natural gas storage caverns in bedded salt. In The 40th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association.

Djizanne, H., Bérest, P., & Brouard, B. (2014). The mechanical stability of a salt cavern used for compressed air energy storage (CAES). In SMRI Spring 2014 Technical Conference. San Antonio, Texas, USA.

Hou, Z. (2003). Mechanical and hydraulic behavior of rock salt in the excavation disturbed zone around underground facilities. International Journal of Rock Mechanics and Mining Sciences, 40(5), 725–738.

Hunsche, U. E. (1993). Failure behaviour of rock salt around underground cavities. In: Proceedings of the 7th symposium on salt, vol 1. pp 59–65.

Labaune, P., Rouabhi, A., Tijani, M., Blanco-Martín, L., & You, T. (2018). Dilatancy criteria for salt cavern design: a comparison between stress-and strain-based approaches. Rock Mechanics and Rock Engineering, 51, 599-611.

Li, H. R. (2015). Experimental study and theoretical analysis on damage characterization of salt rock. (Doctoral dissertation). Chinese Academy of Sciences.
Li, Y. P., Liu, W., Yang, C. H., & Daemen, J. J. K. (2014). Experimental investigation of mechanical behavior of bedded rock salt containing inclined interlayer. International Journal of Rock Mechanics and Mining Sciences, 69, 39–49.
Liang, W. G., Yang, C. H., Zhao, Y. S., Dusseault, M. B., & Liu, J. (2007). Experimental investigation of mechanical properties of bedded salt rock. International Journal of Rock Mechanics and Mining Sciences, 44(3), 400–411.
Liu, J. F., Bian, Y., Zheng, D. W., Wu, Z. D., & Li, T. Y. (2014a). Discussion on strength analysis of salt rock under triaxial compressive stress. Rock and Soil Mechanics, 35(4), 919-925.
Liu, J., Yang, C. H., Wu, W., & Li, Y. P. (2006). Experiment study on short–term strength and deformation properties of rock salts. Chinese Journal of Rock Mechanics and Engineering, 25(S1), 3104–3109.
Liu, W., Muhammad, N., Li, Y. P., Spiers, C. J., Ma, H. L., & Yang, C. H. (2014b). Experimental study of permeability of salt rock and its application to deep underground gas storage. Chinese Journal of Rock Mechanics and Engineering, 33(10), 1953-1961.
Liu, W., Zhang, X., Li, H., & Chen, J. (2020). Investigation on the deformation and strength characteristics of rock salt under different confining pressures. Geotechnical and Geological Engineering, 38, 5703-5717.
Liu, X. Y., Ma, L. J., Ma, S. N., Zhang, X. W., & Gao, L. (2011). Comparative study of four failure criteria for intact bedded rock salt. International Journal of Rock Mechanics and Mining Sciences, 48(2), 341-346.
Lüdeling, C., Günther, R. M., Knauth, M., & Minkley, W. (2015, June). Healing of Rock Salt Damage and Applications. In 49th US Rock Mechanics/Geomechanics Symposium. OnePetro.
Ma, L. J., Liu, X. Y., Fang, Q., Xia, H. M., & Li, Q. S. (2012). An elasto–viscoplastic damage model combined with generalized Hoek-Brown failure criterion for rock salt and its engineering application. Journal of China Coal Society, 37(8), 1299-1303.
Ma, L., Yang, F., Xu, H., & Xie, Z. (2017). Post-yield properties of rock salt using the concept of mobilized strength components and the dilation angle. Geotechnical and Geological Engineering, 35, 2841-2849.
Medina-Cetina, Z., & Rechenmacher, A. (2010). Influence of boundary conditions, specimen geometry and material heterogeneity on model calibration from triaxial tests. International Journal for Numerical and Analytical Methods in Geomechanics, 34(6), 627-643.
Moravej, S., Mutaz, E., Serati, M., & Williams, D. J. (2023). Thermo-Mechanical Coupling of Sandstone Under Biaxial Loading. In 26th World Mining Congress, 2448-2457.
Moravej, S., Mutaz, E., Serati, M., & Williams, D. J. (2023). Coupled Thermo-Mechanical Study of Crack Initiation Stress Threshold in Porous Sandstone. In IOP Conference Series: Earth and Environmental Science (Vol. 1124, No. 1, p. 012022). IOP Publishing.
Rouabhi, A., Labaune, P., Tijani, M., Gatelier, N., & Hévin, G. (2019). Phenomenological behavior of rock salt: On the influence of laboratory conditions on the dilatancy onset. Journal of Rock Mechanics and Geotechnical Engineering, 11(4), 723-738.
Schulze, O., Popp, T., & Kern, H. (2001). Development of damage and permeability in deforming rock salt. Engineering Geology, 61, 163-180.
Serati, M., Alehossein, H., & Erarslan, N. (2016). The Brazilian disc test under a non-uniform contact pressure along its thickness. Rock Mechanics and Rock Engineering, 49, 1573-1577.
Serati, M., Jakson, N., Asche, H., Basireddy, S., & Malgotra, G. (2022). Sustainable shotcrete production with waste glass aggregates. SN Applied Sciences, 4(3), 82.
Serati, M., Masoumi, H., Williams, D. J., Alehossein, H., & Roshan, H. (2018, June). Some new aspects on the diametral point load testing. In 52nd US Rock Mechanics/Geomechanics Symposium. OnePetro.
Spiers, C., Peach, C., & Brzesowsky, R. (1989). Long-term rheological and transport properties of dry and wet salt rocks: final report. Office for Official Publications of the European Communities.
Stormont, J.C. (1997). In situ gas permeability measurements to delineate damage in rock salt. International Journal of Rock Mechanics and Mining Sciences, 34, 1055-1064.
Van Sambeek, L. L., Ratigan, J. L., & Hansen, F. D. (1993). Dilatancy of rock salt in laboratory tests. International Journal of Rock Mechanics, Mining Sciences & Geomechanics Abstracts, 30(7), 735–738.
Ye, L., Chen, F., Xue, T., & Wang, W. (2022, June). Study on Strength of Rock Salt with Mudstone Based on the Hoek-Brown Criterion. In 56th US Rock Mechanics/Geomechanics Symposium. OnePetro.