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The Role of Environmental Conditions in the Self-Healing Behaviour of Rock Salt

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Abstract

Salt caverns are among the most viable options for hydrogen storage due to their safety and cost efficiency. Particularly for large-scale hydrogen storage, the self-healing ability of rock salt is crucial for maintaining cavern integrity, ensuring safety, and supporting the long-term viability of these storage systems. This study investigates the factors influencing self-healing in rock salt, focusing on the effects of high temperature, high humidity, and their combinations.

Damage was induced in rock salt samples through uniaxial compression, applied up to 50% of the uniaxial compressive strength (UCS), to account for the effect of initial damage. Ultrasonic technology was used to monitor self-healing by measuring changes in the velocity of longitudinal waves through the damaged samples. Wave velocity was also tracked during loading to evaluate the stress-strain response of healed samples under load.

The post-self-healing behaviour was assessed by analyzing UCS under various environmental conditions. Results indicate that increasing temperature alone negatively affects self-healing efficiency. However, the combination of elevated temperature and high humidity significantly enhances self-healing, promoting greater damage closure and strength recovery. The application of cyclic moisture at high temperatures further optimized self-healing performance. These findings underscore the critical role of environmental conditions in enhancing the recovery potential of rock salt, with significant implications for energy storage and geotechnical applications.

Keywords

Rock salt, Self-healing, Ultrasonic monitoring, Uniaxial Compressive Strength, Stress-strain response

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1 Introduction

Hydrogen storage in rock salt caverns offers a promising solution to the growing demand for sustainable and low-emission energy sources. The unique properties of rock salt, such as its impermeability and structural stability, make it an ideal candidate not only for hydrogen storage but also for other applications, including natural gas, petroleum products, compressed air, carbon dioxide, and hazardous waste disposal (Bays, 1962; Fokker, 1995; Ozarslan, 2012; Djizanne et al., 2014; Moravej et al., 2023, Serati et al., 2014, 2020; Thoms & Gehle, 2000; Xu et al., 2018).

Rock salt is primarily known for its compressive strength and unique creep behaviour, however, its tensile strength also plays a key role in its sealing capability, fracture development, and long-term deformation and closure behaviour of salt caverns under cyclic loading. In addition to its mechanical advantages, rock salt exhibits a remarkable self-healing ability under specific thermomechanical conditions. This property is particularly significant for subsurface energy storage, where maintaining structural integrity and low permeability is essential. During the construction and operation of salt caverns, stress and fluid pressure changes can induce microcracks and fissures, especially in low-confinement environments (Houben et al., 2013; Wang et al., 2016). These microcracks can compromise the mechanical stability and impermeability of the cavern walls, leading to gas escape and reduced performance.

Salt caverns, typically located at depths of 1,500 to 2,500 meters, are subjected to high temperatures (up to 90 °C) and significant geological stresses (Moravej et al, 2023). The interplay between temperature, stress, and the geochemical environment not only influences the structural integrity of the caverns but also impacts their self-healing potential. Understanding these factors is crucial for the safe and efficient design of storage facilities and for leveraging the self-healing mechanisms of rock salt to ensure long-term stability and impermeability.

The self-healing of rock salt involves the closure and healing of cracks, which restore mechanical properties and reduce permeability. Despite extensive research, the detailed mechanics of self-healing under varying environmental conditions remain unclear. Key factors influencing self-healing include stress, temperature, moisture, and fracture morphology. Confining pressure, for example, accelerates healing by promoting crack closure and improving material stiffness. Brodsky and Munson (1994) demonstrated that volumetric strain decreases with increasing pressure, leading to faster void closure and enhanced structural integrity.

Temperature also plays a pivotal role, facilitating recrystallization and grain boundary migration - key mechanisms in the self-healing process. Studies have shown that higher temperatures accelerate volumetric strain reduction and mechanical recovery (Brodsky & Munson, 1994; Chen et al., 2013). Similarly, moisture significantly enhances self-healing by promoting chemical healing and recrystallization. Chen et al. (2020) demonstrated that brine solutions effectively heal microcracks, emphasizing the role of fluids in mineral transport and grain growth.

Other factors, such as crack size, orientation, and initial damage level, also influence healing efficiency. Smaller, less complex fractures tend to heal more readily due to lower surface energy requirements and crack tip dissolution (Chen et al., 2018). Conversely, the presence of impurities can hinder healing by obstructing grain boundary migration and chemical processes (Chen et al., 2013).

This study evaluates the effects of temperature and humidity on the self-healing and mechanical response of rock salt, contributing to a deeper understanding of the factors that influence its recovery potential under subsurface conditions.

2 Material and methods

2.1 Material and instrument set-up

High-purity rock salt specimens (98% NaCl) were obtained from the Khewra Salt Mine in Pakistan. The samples were prepared into 50 mm cubes, with smooth and even surfaces achieved through grinding to ensure uniformity during testing. All experiments were conducted using an Instron Machine at the University of Queensland, applying a constant loading rate of 15 kN/min (equivalent to 0.1 MPa/s). (Fig.1 a and b)

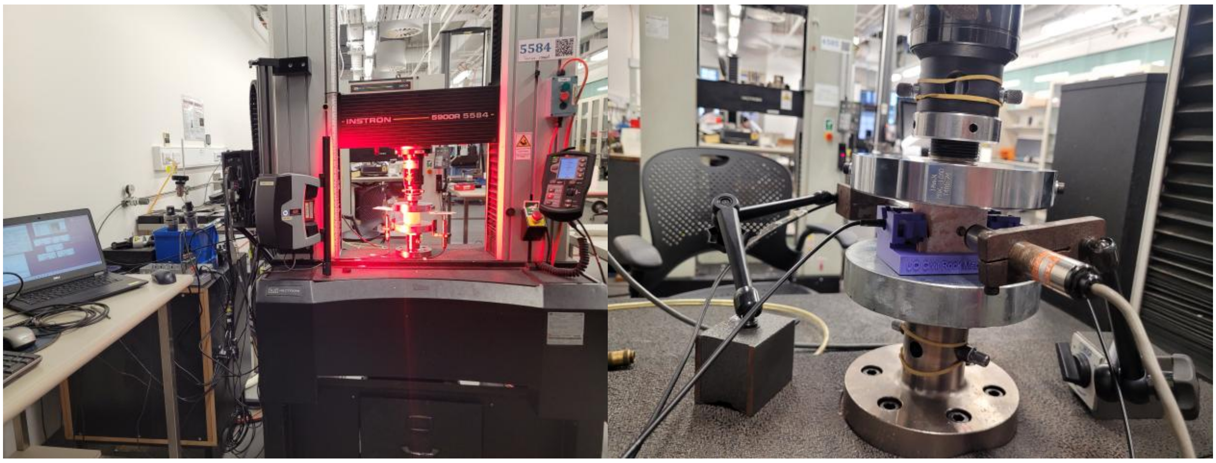


Fig. 1: (a) Instron Machine for inducing damage and UCS testing, (b) Ultrasonic sensors and LVDTs attached to the sample.

Under uniaxial compressive strength (UCS) testing conditions, rock salt exhibited strain-softening and brittleness. The average UCS for undamaged rock salt samples was measured at 43 MPa, with an axial strain exceeding 5% (Fig. 2). Lateral displacement was recorded using LVDTs, while an ultrasonic device was employed to monitor damage levels by measuring changes in wave velocity.

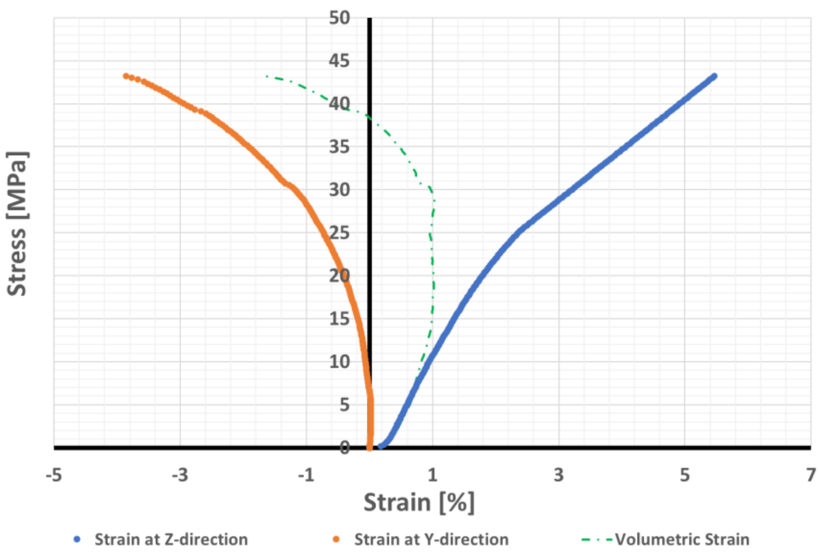


Fig. 2. Uniaxial compressive strength (UCS) test results for rock salt samples.

Intact samples were damaged by loading to 50% of their UCS and then subjected to various self-healing scenarios to assess the effects of temperature and humidity. The extent of damage before and after healing was measured to evaluate the influence of these parameters.

2.2 Damage assessment

The degradation and recovery of rock salt were quantitatively evaluated using ultrasonic testing, which utilizes wave velocity as an index of material integrity. The damage parameter D, a dimensionless value, was used to quantify the extent of structural degradation:

D=0: Represents a completely undamaged state, retaining the material's pristine properties.
D=1: Represents complete structural damage, characterized by significant microcracks, voids, or deformations

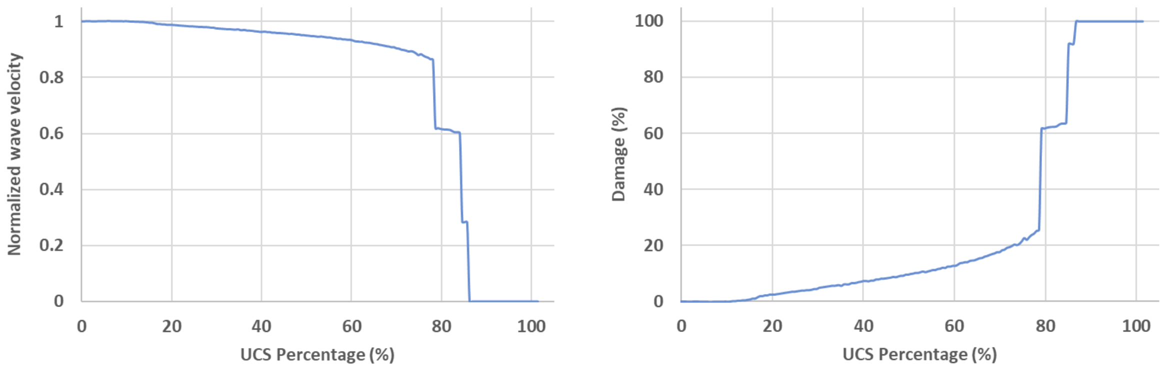
The damage parameter is defined by Eq. 1 as follows:

$$D = 1 - (\frac{V_{pd}}{V_p})^2 \quad (1)$$

Where

D	The damage value of the material
V_p	The wave velocity of the sample under an undamaged state.
V_{pd}	The Wave velocity of the damaged material.

This formula is derived from the reduction in wave velocity caused by structural damage and incorporates a squared term to account for proportional energy dissipation during wave propagation through damaged media. Wave velocities were monitored in real-time, enabling the calculation of damage at any loading stage. (Fig 3a and 3b)



a b

Fig. 3 a) Normalized wave velocity versus loading, b) Damage calculated based on ultrasonic measurements versus loading.

For self-healing analysis, samples were pre-damaged to 50% of UCS.

2.3 Healing

Self-healing efficiency was quantified using the relative reduction in damage, calculated using Eq. 2 as:

$$\tau = \frac{D_0 - D_{fin}}{D_0} \quad (2)$$

Where	D_0	The initial damage value,
	D_{fin}	The final damage value after the healing process,
	H	Healing percentage

A healing value of 1 indicates complete recovery, where the material returns to its undamaged state, while a healing value of 0 signifies no recovery. This approach enabled the evaluation of healing efficiency under varying environmental conditions, providing insight into the influence of temperature and humidity on rock salt's recovery potential.

3 Results

This study investigates the factors influencing the self-healing behavior of rock salt through experimental conditions designed to evaluate the effects of temperature, humidity, and time. These scenarios explore the individual contributions of each parameter and their interactions in the self-healing process. The results are presented below, categorized by the specific conditions applied

3.1 High-Temperature Recovery:

To evaluate the effect of temperature on self-healing, three sets of samples were prepared: one set was left to recover at ambient temperature (30°C) in a sealed bag, another set was held in an oven at 60°C for 72 hours, and a third set was held in an oven at 100°C for 72 hours. Figures 4a and 4b illustrate the influence of temperature on the self-healing behaviour and mechanical recovery of rock salt. The results indicate that the self-healing percentage decreases with increasing temperature.

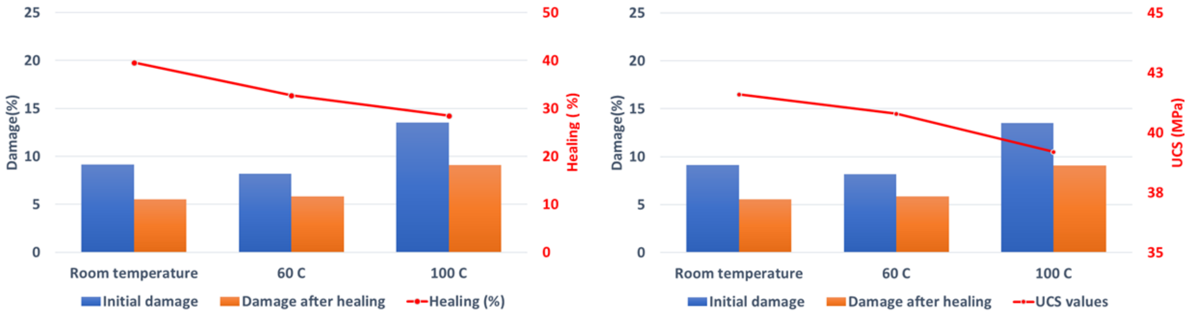


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Fig. 4 a) Healing percentage for rock salt under different conditions at 50% UCS, and b) UCS values correspond to 50% UCS recovery tests.

At room temperature (30°C), the natural recovery of damaged rock salt without external intervention resulted in the highest healing percentage, characterized by a significant reduction in residual damage. This outcome serves as a baseline for evaluating the effects of elevated temperatures on self-healing.

Samples subjected to elevated temperatures of 60°C and 100°C exhibited lower healing percentages compared to room temperature. The decline in self-healing efficiency at higher temperatures highlights a negative correlation between temperature and self-healing percentage in the absence of moisture (Figure 4a).

The observed decrease in healing percentage at higher temperatures is likely due to thermally induced changes in microstructural processes. Elevated temperatures accelerate mechanisms such as recrystallization and stress relaxation. While these processes aid in the initial reduction of damage, they may limit the overall extent of healing by altering microstructural pathways critical for damage closure, particularly in the absence of sufficient moisture.

The uniaxial compressive strength (UCS) results (Figure 4b) support this trend. Although elevated temperatures promote some degree of mechanical recovery, the UCS values do not correspond to higher healing percentages, suggesting that temperature-driven recovery is insufficient to fully restore material integrity without external interventions such as moisture.

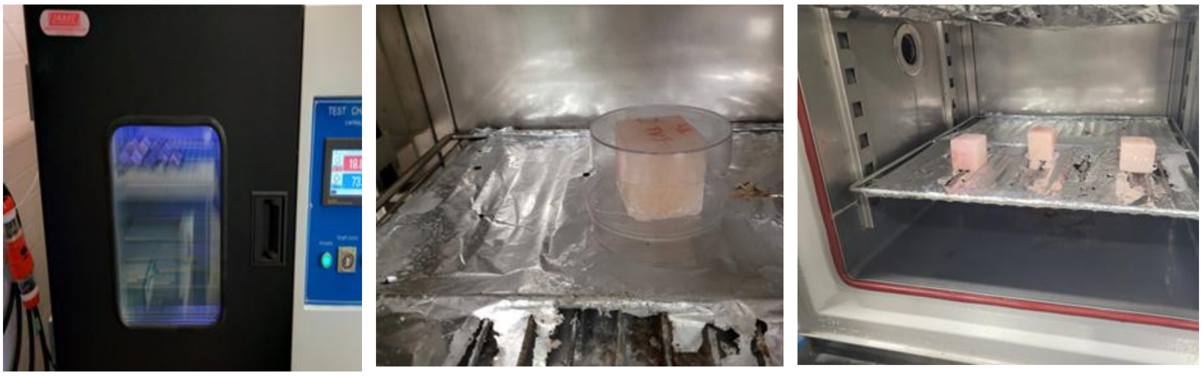
In summary, these findings indicate a negative correlation between temperature and self-healing percentage in the absence of moisture. This emphasizes the complex interplay between thermal conditions and microstructural mechanisms governing self-healing. High temperature creates more unfavourable damage recovery in the drying process.

3.2 Constant High Humidity and Temperature:

To evaluate the combined effects of high temperature and moisture on the self-healing process of rock salt, samples were subjected to a constant temperature of 75°C and 90% relative humidity. These conditions were maintained in an environmental chamber, specifically designed to control both temperature and humidity.

Due to the high relative humidity (90%), measures were taken to prevent excessive deliquescence on the end faces of the specimens, which could otherwise interfere with the testing process:

- Glass dishes were used to cover the specimens, effectively blocking direct exposure to moisture.
- Vaseline was applied to the top and bottom faces of the specimens to create a moisture-resistant barrier.



a b c

Fig. 5 a) Environmental chamber used for testing, b) Specimen covered with glass dishes to block moisture, c) Samples placed inside the environmental chamber.

The results, presented in Figures 6a and 6b, highlight the significant influence of moisture in conjunction with temperature on the recovery process.

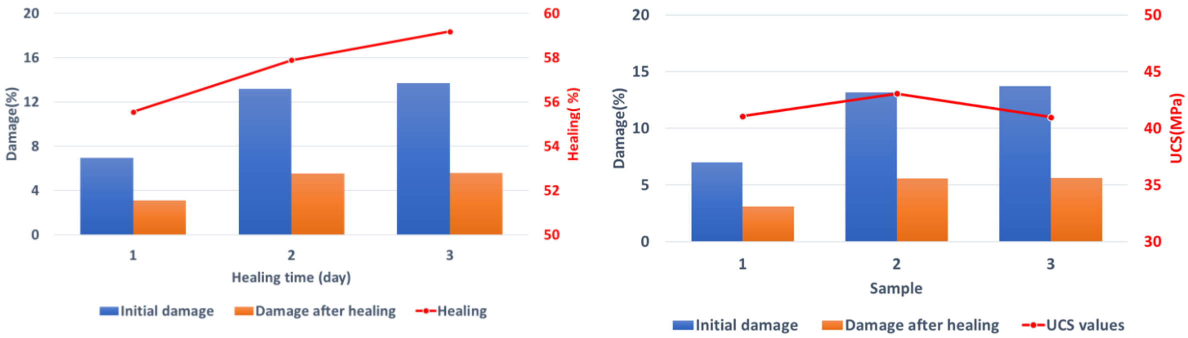


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Fig. 6. a. Healing percentage versus time for rock salt under high humidity and temperature conditions, b. UCS values for healed samples subjected to high humidity and temperature at different time intervals.

These findings indicate that prolonged exposure to high humidity significantly enhances the effectiveness of damage recovery, likely driven by moisture-assisted mechanisms such as dissolution-precipitation processes and enhanced crack closure.

Moreover, the increase in uniaxial compressive strength (UCS) with healing demonstrates that the combination of moisture and elevated temperature not only accelerates the healing process but also contributes to the partial restoration of the mechanical integrity of the rock salt. This highlights the synergistic role of humidity and temperature in promoting microstructural recovery, which in turn contributes to strength enhancement.

3.3 Cyclic Humidity and High Temperature:

In another scenario, samples were subjected to cyclic humidity variations ranging from 90% to 40% at a constant temperature of 60°C. This setup closely replicates the fluctuating moisture conditions typically observed in salt caverns (Zeng et al., 2024).

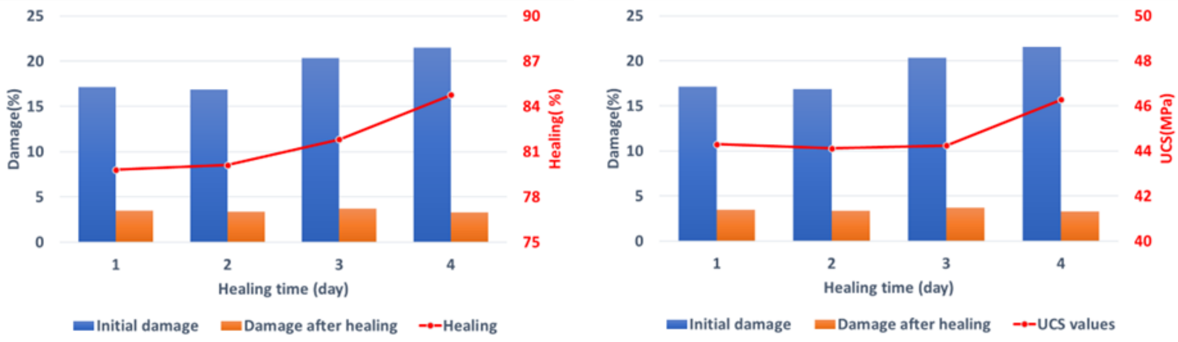

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Fig. 7 a. Healing percentage versus time for rock salt under high humidity and temperature conditions, b. UCS values for healed samples subjected to high humidity and temperature at different time intervals.

The results illustrate that cyclic humidity variations enhance the self-healing behavior and mechanical properties of rock salt over time (Figures 7a and 7b). The effectiveness of cyclic moisture conditions can be attributed to periodic dissolution and recrystallization processes, which are instrumental in facilitating crack closure and damage healing. These processes enable dynamic microstructural adjustments that contribute to both damage recovery and strength restoration. These findings are particularly relevant for the long-term stability of salt caverns utilized in energy storage applications, where fluctuating environmental conditions are prevalent. Understanding the impact of cyclic humidity on self-healing behaviour is essential for optimizing the design and maintenance of subsurface facilities, ensuring their stability and performance over extended operational lifetimes.

4 Conclusion

This study investigated the self-healing behaviour of rock salt under varying environmental conditions-temperature, humidity, and time - to evaluate its recovery potential for energy storage and geotechnical applications. The key findings are as follows:

Temperature Effects: Elevated temperatures reduced the self-healing percentage in the absence of humidity. Although temperatures of 60°C and 100°C facilitated partial mechanical recovery, healing efficiency declined compared to ambient conditions. This highlights the complex interplay between thermal processes and microstructural changes governing damage recovery.

Humidity Influence: While increased humidity promotes self-healing, cyclic humidity enhances it more effectively than constant conditions. Cyclic variations accelerate dissolution and recrystallization by shifting equilibrium. Evaporation during the dry stage increases supersaturation, driving recrystallization, while moisture in the humid stage facilitates halite dissolution. This process accelerates healing, forming stronger microstructures in less time.

Time Dependency: Prolonged exposure improved both damage recovery and uniaxial compressive strength (UCS) under all test conditions. This underscores the importance of sustained environmental stability to maximize the self-healing potential of rock salt over extended periods.

These findings emphasize the pivotal role of environmental factors - particularly humidity and time - in enhancing the self-healing capabilities of rock salt. This is especially significant for designing salt caverns and other subsurface facilities in salt deposits, where long-term stability and structural integrity are critical. Further research is recommended to explore the mechanisms of humidity-assisted healing and optimize operational conditions for practical applications.

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