



Delft University of Technology

Document Version

Final published version

Citation (APA)

Fu, S. (2026). *Evolution of rock salt fracture geometry and mechanical properties during fluid–rock interactions*. [Dissertation (TU Delft), Delft University of Technology]. <https://doi.org/10.4233/uuid:3d90e5ac-17f0-490d-b180-3e46aa81ffff>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

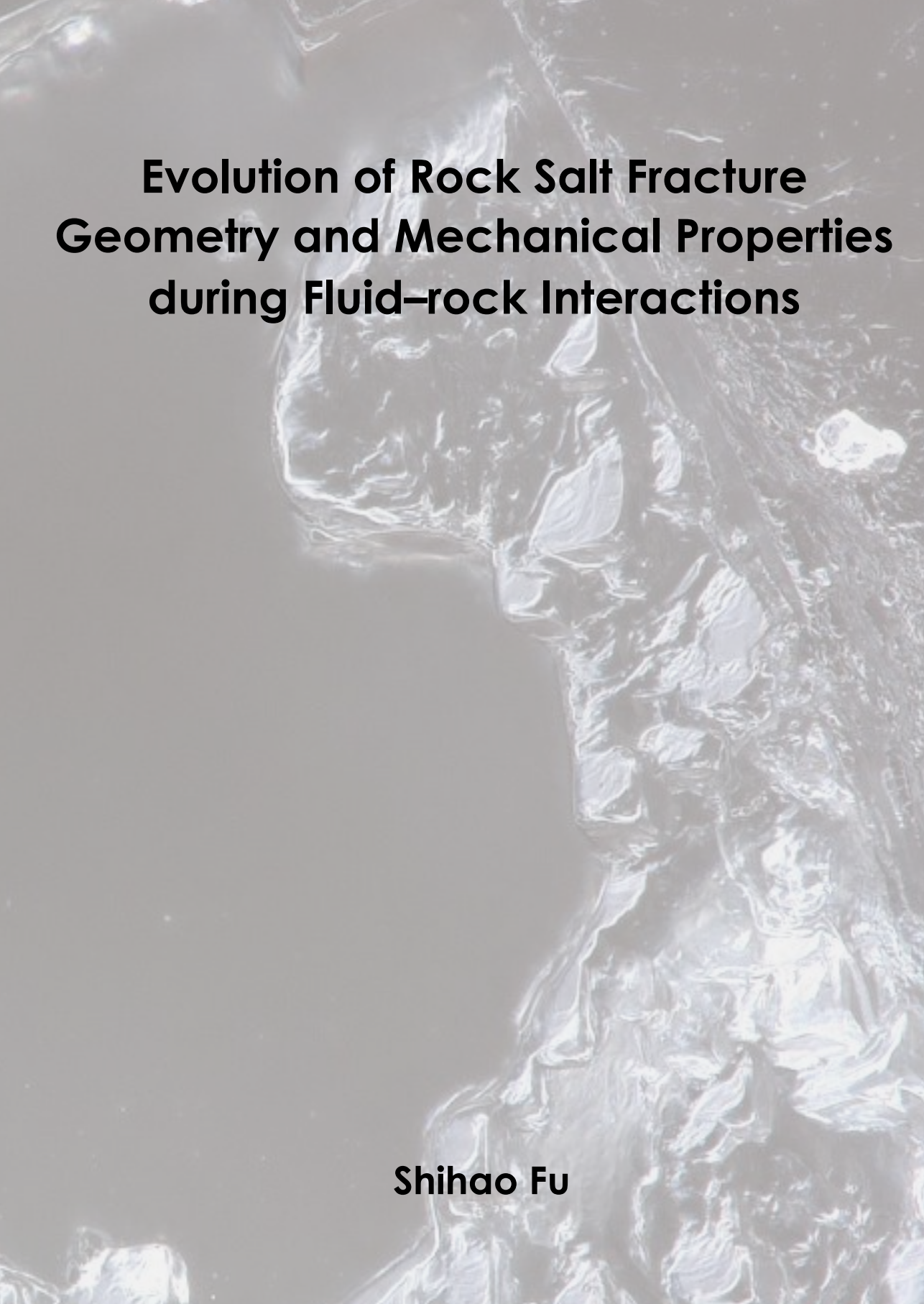
Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

A grayscale microscopic image of a rock salt fracture. The image shows a complex, irregular fracture network with various sub-parallel and branching structures. The fracture surfaces appear rough and textured, with some areas showing more pronounced folding or layering. The overall tone is dark gray, with lighter gray highlights defining the fracture geometry.

Evolution of Rock Salt Fracture Geometry and Mechanical Properties during Fluid-rock Interactions

Shihao Fu

**EVOLUTION OF ROCK SALT FRACTURE
GEOMETRY AND MECHANICAL PROPERTIES
DURING FLUID–ROCK INTERACTIONS**

EVOLUTION OF ROCK SALT FRACTURE GEOMETRY AND MECHANICAL PROPERTIES DURING FLUID–ROCK INTERACTIONS

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology,
by the authority of the Rector Magnificus, Prof. dr. ir. H. Bijl,
chair of the Board for Doctorates
to be defended publicly on
Thursday 26 February 2026 at 10:00

by

Shihao FU

This dissertation has been approved by the promotor.

Composition of the doctoral committee:

Rector Magnificus, Prof. dr. D.F. Bruhn, Dr. A.M.H. Pluymakers, Dr. ir. A.C. Dieudonné,	Chairperson Delft University of Technology, promotor Delft University of Technology, copromotor Delft University of Technology, copromotor
Independent members: Prof. Dr. ir. L.V. Socco, Prof. L. Wang, Dr. L. Blanco-Martin, Em. Prof. Dr. C.J. Spiers,	Delft University of Technology China University of Petroleum (Bei Jing), China Mines Paris, PSL Research University, France Utrecht University
Prof. Dr. P. J. Vardon,	Delft University of Technology, reserve member

This research was conducted in the Rock Mechanics and Petrophysics Laboratory at Delft University of Technology and was supported by the Chinese Scholarship Council (CSC No. 202106440022).



Key words: Energy storage, Salt Cavern, Damage Zone, Fractures, Dissolution-transport process, Healing behaviour, Surface roughness, Finite element method

Printed by: ProefschriftMaken

Front & Back: Design by the author

Copyright © 2026 by S. Fu

ISBN 978-94-6518-243-8

An electronic copy of this dissertation is available at

<http://repository.tudelft.nl/>.

Only by knowing why we came can we know why we must go
知所从来，方明所往.

Contents

SUMMARY	XI
SAMENVATTING	XIII
1. Introduction	1
1.1 Motivation	4
1.2 Fluid-rock interactions in rock salt fractures.....	5
1.2.1 Dissolution and transport versus sealing processes	5
1.2.2 Evolution of mechanical properties of fractures	8
1.2.3 Micro-mechanisms active in salt deformation.....	9
1.3 Numerical methods and platforms	11
1.4 Objectives and outline	12
1.5 References.....	14
2. Visualization and quantification of dissolution and transport process in rock salt fractures	17
2.1 Introduction	18
2.2 Methods and materials	21
2.2.1 Fabrication of fracture channel.....	22
2.2.2 Experimental setup and procedures	23
2.2.3 Image processing method	25
2.2.4 Coupled reactive and transport model.....	28
2.3 Results.....	30
2.3.1 Fracture geometry evolution.....	30
2.3.2 Dissolution mass and rates	34
2.3.3 Coupled reactive and transport model.....	37
2.4 Discussion	40
2.4.1 Effect of initial geometry	40
2.4.2 Effect of fluid conditions	42
2.4.3 Implications	43
2.5 Conclusions	44
2.6 References.....	45
3. Fracture healing and surface roughness evolution in rock salt	47
3.1 Introduction	48
3.2 Methodology	50
3.2.1 Sample preparation	50

3.2.2 Direct shear box test	51
3.2.3 Data processing	52
3.3 Results.....	56
3.3.1 Mechanical results	56
3.3.2 Microstructural results.....	63
3.4 Discussion	68
3.4.1 Stress response during shearing.....	68
3.4.2 Healing mechanisms	70
3.4.3 Implications for energy storage.....	72
3.5 Conclusions	73
3.6 References	74
4. Healing behaviour of rock salt fractures with varying surface roughness	77
4.1 Introduction	78
4.2 Methodology	79
4.2.1 Sample preparation	79
4.2.2 Direct shear box experiments	80
4.2.3 Data processing	80
4.3 Results.....	82
4.3.1 Healing strength	82
4.3.2 Friction angle	84
4.3.3 Microstructural analysis.....	85
4.4 Discussion and conclusions.....	86
4.5 References	88
5. Analysis of rock salt healing within a cohesive zone modelling framework.	89
5.1 Introduction	90
5.2 Elasto-plastic cohesive zone model of Caballero et al. (2008)	92
5.2.1 Model formulation	92
5.2.2 Numerical integration	95
5.2.3 Numerical verification and validation.....	98
5.2.4 Extension of the model of Caballero et al. (2008) to account for healing effect	105
5.3 Conclusions	111
5.4 References	113
6. Conclusions and recommendations	115
6.1 Conclusions	115
6.1.1 Dissolution of rock salt fractures	115

6.1.2 Healing of fractures in rock salt	116
6.1.3 Long-term strength recovery of rock salt fractures.	116
6.1.4 Implications for salt caverns	117
6.2 Recommendations for future research.....	118
6.2.1 Improving visualization of fracture evolution	118
6.2.2 Investigating fracture roughness effect in dissolution	119
6.2.3 Exploring sealing behaviour of rock salt fractures under stress	119
6.2.4 Recovery of the tensile strength upon healing	120
6.2.5 Healing under open system conditions with normal stress.....	120
6.2.6 Incorporating acoustic emission monitoring in shear experiments	121
6.2.7 Incorporating the thermal and stress effects into interface model	121
6.3 References	122
APPENDIX A	123
APPENDIX B	128
APPENDIX C	130
ACKNOWLEDGEMENT.....	131
CURRICULUM VITAE	133
LIST OF PUBLICATIONS	135
JOURNALS	135
CONFERENCES	135

SUMMARY

Rock salt caverns offer a promising subsurface engineering solution for CO₂ storage, waste disposal, compressed air energy storage, and hydrogen storage, owing to their substantial extent, extremely low permeability, and minimal porosity. The long-term containment of injected gases, fluids or disposed materials relies on the integrity of cavern seals. However, fractures in the damaged zone formed during the wellbore drilling phase, storage operations, or the abandonment phase can compromise system integrity by acting as preferential flow paths and mechanically weak zones. This poses a challenge to the safety of subsurface storage throughout the operational lifespan of a salt cavern. Understanding the evolution of these fractures in terms of their physical and mechanical properties is therefore essential. In this thesis, we adopt an integrated experimental-numerical approach to investigate both the dissolution behaviour and mechanical recovery of rock salt fractures.

During the leaching period, the walls of a rock salt cavern are exposed to undersaturated brine. Fractures in contact with undersaturated brine are expected to undergo dissolution, with the dissolved ions being transported and potentially precipitating at a further location. This process alters the geometry of the fractures over time. We develop a flow-visualization experimental setup at the decimetre scale, combined with quantitative measurement techniques, to investigate how initial fracture geometry, salt concentration, and flow rate influence the evolution of rock salt fracture channels. The results show that dissolution within fractures is heterogeneous, with increased dissolution near the inlet and along fracture corners due to advection-dominated flow, leading to progressive smoothing of fracture surfaces. Fractures with larger initial surface areas exhibit higher dissolution rates and greater total mass loss compared to those with smaller surface areas. Moreover, the dissolution patterns observed in this study differ from those typically reported at the microscale. To further interpret the experimental observations, a coupled reactive transport model is developed using COMSOL Multiphysics to simulate fluid velocity distribution and solute concentration.

Following the leaching process, salt caverns are employed for energy storage and extraction, during which the surrounding rock salt, particularly near the upper and lower cavern walls, is subjected to alternating dry and wet conditions. Given rock salt's inherent healing capabilities (i.e., mechanical recovery), we investigate the shear strength recovery of rock salt fractures through direct shear box experiments. The evolution of fracture surface geometry is further examined using digital microscopy and microcomputed tomography (micro-CT). Results reveal a log-linear relationship between healing and time, with wet conditions exhibiting a recovery rate approximately seven times greater than that under dry conditions, consistent with time-dependent frictional healing laws observed in gouge. Healing in dry samples can be attributed to plastic flow. Additionally, dynamic behaviour is characterised by an increase in the residual friction coefficient over time. Healing in wet samples can be attributed to pressure solution, recrystallisation, and possibly surface energy minimisation processes. A difference in stick-slip behaviour in terms of frequency and stress drop is observed between dry and wet samples. This difference may be due to the applicability of a distance-dependent

model of stick-slip behaviour in dry conditions and a velocity-dependent model in wet conditions.

In addition, the effect of initial fracture surface roughness on healing behaviour is examined by preparing samples with smooth and rough surfaces. Under dry conditions, strength recovery is limited and observed only in smooth fractures. In wet conditions, smooth fractures exhibit substantial healing, whereas rough fractures show only minor improvement. These findings demonstrate a clear inhibitory effect of surface roughness on strength recovery in fully saturated environments. This effect is attributed to the larger aperture in rough surface samples, which hinders crystal growth across the fracture and impedes bridging between opposing surfaces.

Finally, an existing elasto-plastic constitutive law is shown to also be capable to simulate damage and healing behaviour of rock salt fractures, based on a cohesive zone model framework, enabling the prediction of strength recovery over time. Specifically, fracture initiation is governed by a hyperbolic yield surface in the $\sigma_n - \tau_s$ stress plane. The shrinkage (damage stage) and expansion (healing stage) of the yield surface are governed by two history-dependent variables: an internal variable (W_{cr}) represents the dissipated fracturing (plastic) work, as established in existing models. The expansion (healing stage), in contrast, is governed by an external variable (H_t), which we propose here to represent the progressive recovery of the mechanical properties of rock salt fractures over time. The key features of the existing formulation are demonstrated through single-element tests under various sequences of mechanical loading. Simulations with and without healing show good agreement with laboratory results for both non-healed and healed samples, confirming the model's ability to capture the essential characteristics of fracture healing in rock salt. Additional simulations over healing periods from years to decades are performed to assess long term recovery behaviour.

This thesis examines the evolution of the physical properties of rock salt fractures during dissolution, the mechanical recovery of fractures, and the associated microstructural changes of fracture surfaces, using both experimental and numerical approaches. The findings provide insights into the design and performance of salt caverns for energy storage and radioactive waste disposal.

SAMENVATTING

Zoutcavernes vormen een veelbelovende ondergrondse technologie voor CO₂-opslag, afvalverwijdering, opslag van gecompriëerde lucht en waterstofopslag, dankzij hun grote omvang, extreem lage permeabiliteit en geringe porositeit. De langdurige insluiting van geïnjecteerde gassen, vloeistoffen of opgeslagen materialen is afhankelijk van de integriteit van de caverneseals. Scheuren in de beschadigde zone, die kunnen ontstaan tijdens het boren van de put, de opslagoperaties of de buitengebruikstellingsfase, kunnen de systeemintegriteit echter aantasten doordat ze fungeren als voorkeursstromingspaden en mechanisch zwakke zones. Dit vormt een uitdaging voor de veiligheid van ondergrondse opslag gedurende de volledige levensduur van een zoutcaverne. Inzicht in de evolutie van deze breuken, in termen van hun fysische en mechanische eigenschappen, is daarom essentieel. In dit proefschrift hanteren wij een geïntegreerde experimenteel-numerieke aanpak om zowel het oplossingsgedrag als het mechanisch herstel van zoutbreuken te onderzoeken.

Tijdens de uitlooperperiode worden de wanden van een steenzoutcaverne blootgesteld aan onverzadigde pekkel. Breuken die in contact staan met onverzadigde pekkel zullen naar verwachting oplossen, waarbij de opgeloste ionen worden getransporteerd en mogelijk elders neerslaan. Dit proces verandert in de loop van de tijd de geometrie van de breuken. Wij hebben een experimentele opstelling op decimeterschaal ontwikkeld voor stroomvisualisatie, gecombineerd met kwantitatieve meetmethoden, om te onderzoeken hoe de initiële breukgeometrie, zoutconcentratie en stroomsnelheid de evolutie van breukkanalen in steenzout beïnvloeden. De resultaten laten zien dat de oplossing binnen breuken heterogeen verloopt, met verhoogde oplossing nabij de inlaat en langs breukhoeken door advection-geïnduceerde stroming, wat leidt tot een geleidelijke afvlakking van de breukoppervlakken. Breuken met een groter oorspronkelijk oppervlak vertonen hogere oplossingsnelheden en een groter totaal massaverlies dan breuken met een kleiner oppervlak. Bovendien verschillen de oplossingspatronen die in dit onderzoek zijn waargenomen van die welke doorgaans op microschaal worden gerapporteerd. Ter verdere interpretatie van de experimentele waarnemingen is een gekoppeld reactief transportmodel ontwikkeld met COMSOL Multiphysics om de vloeistofsnelheidsverdeling en opgeloste-stofconcentratie te simuleren.

Na het uitlooperproces worden zoutcavernes gebruikt voor energieopslag en -winning, waarbij het omringende steenzout, met name nabij de bovenste en onderste cavernemuren, wordt blootgesteld aan afwisselend droge en natte omstandigheden. Gezien het inherente zelfherstellend vermogen van steenzout (d.w.z. mechanisch herstel), onderzoeken wij het herstel van de schuifsterkte van steenzoutbreuken met behulp van directe schuifproeven. De evolutie van het breukoppervlak wordt verder onderzocht met digitale microscopie en micro-computertomografie (micro-CT). De resultaten tonen een log-lineair verband tussen herstel en tijd, waarbij onder natte omstandigheden een herstelsnelheid wordt waargenomen die ongeveer zeven keer hoger is dan onder droge omstandigheden, in overeenstemming met de tijdsafhankelijke wrijvingsherstelwetten die in gouge zijn waargenomen. Het herstel in droge monsters kan worden toegeschreven aan plastische vloeï. Daarnaast wordt het dynamisch gedrag gekenmerkt door een toename van de residuele wrijvingscoëfficiënt in de tijd. Het herstel

in natte monsters kan worden toegeschreven aan drukoplossing, herkristallisatie en mogelijk processen van oppervlakte-energiereductie. Er wordt een verschil in stick-slipgedrag waargenomen tussen droge en natte monsters, zowel in frequentie als in spanningsval. Dit verschil kan worden verklaard door de toepasbaarheid van een afstandsafhankelijk model van stick-slipgedrag onder droge omstandigheden en een snelheidsafhankelijk model onder natte omstandigheden.

Daarnaast wordt het effect van de initiële breukoppervlakteruwheid op het genezingsgedrag onderzocht door monsters met gladde en ruwe oppervlakken te prepareren. Onder droge omstandigheden is het herstel van de sterkte beperkt en wordt dit alleen waargenomen bij gladde breuken. In natte omstandigheden vertonen gladde breuken aanzienlijk herstel, terwijl ruwe breuken slechts een geringe verbetering laten zien. Deze bevindingen tonen een duidelijk remmend effect van oppervlakteruwheid op het herstel van de sterkte in volledig verzadigde omgevingen. Dit effect wordt toegeschreven aan de grotere spleetwijdte bij monsters met een ruw oppervlak, waardoor kristalgroei over de breuk wordt belemmerd en de vorming van bruggen tussen tegenoverliggende oppervlakken wordt verhinderd.

Ten slotte wordt aangetoond dat een bestaande elastoplastische constitutiewet ook in staat is het schade- en herstelgedrag van steenzoutbreuken te simuleren binnen een cohesiezone-modelraamwerk, waarmee de sterkteherstel over de tijd kan worden voorspeld. De initiatie van breuken wordt specifiek bepaald door een hyperbolisch vloeivlak in het $\sigma_n - \sigma_s$ spanningsvlak. De inkrimping (schadefase) en uitbreiding (herstelfase) van het vloeivlak worden bestuurd door twee geschiedenisafhankelijke variabelen: een interne variabele (W_{cr}) vertegenwoordigt het gedissipeerde breuk-(plastische) werk, zoals vastgesteld in bestaande modellen. De uitbreiding (herstelfase) daarentegen wordt bestuurd door een externe variabele (H_t), die wij hier voorstellen als representatie van het geleidelijke herstel van de mechanische eigenschappen van steenzoutbreuken in de tijd. De belangrijkste kenmerken van de bestaande formulering worden aangetoond aan de hand van enkelelementtesten onder verschillende reeksen van mechanische belasting. Simulaties met en zonder herstel tonen een goede overeenstemming met laboratoriumresultaten voor zowel niet-genezen als genezen monsters, wat de capaciteit van het model bevestigt om de essentiële kenmerken van breukherstel in steenzout te reproduceren. Aanvullende simulaties over herstelperioden van jaren tot decennia zijn uitgevoerd om het langetermijngedrag van het herstel te beoordelen.

Dit proefschrift onderzoekt de evolutie van de fysische eigenschappen van steenzoutbreuken tijdens oplossing, het mechanische herstel van breuken en de bijbehorende microstructurele veranderingen van breukoppervlakken, met behulp van zowel experimentele als numerieke benaderingen. De bevindingen bieden waardevolle inzichten voor het ontwerp en de prestaties van zoutcavernes voor energieopslag en de opslag van radioactief afval.

1. Introduction

The global transition from conventional energy sources to cleaner, more sustainable alternatives has intensified the demand for efficient energy storage solutions, which has led to increased attention for salt caverns. Technologies such as natural gas storage (Lord, 2009, CO₂ storage (Mehr et al., 2024), hydrogen energy (Williams et al., 2022; Kruck et al., 2023; Patanwar et al., 2024) and compressed air energy storage (CAES) (He et al., 2017; King et al., 2021) have emerged as potentially pivotal technologies to address challenges in energy centralization, supply demand balancing (for example, hydrogen storage to match seasonal energy needs), and ensuring long-term economic efficiency (Ozarslan, 2012; Lehtveer et al., 2017). A variety of energy storage methods has already been implemented worldwide (Liu et al., 2023; Kumar et al., 2023). Among these, underground salt caverns have garnered particular interest due to their favourable geomechanical properties (Bérest & Brouard, 2003; Kumar et al., 2023; Blanco-Martín et al., 2024). Salt caverns offer high injectivity and deliverability rates, and the surrounding formation will have excellent sealing capabilities due to minimal permeability, making them ideal for storing energy such as crude oil, natural gas, or hydrogen (Figure 1.1 (a)). Furthermore, salt formations are a potential host formation for the disposal of radioactive waste, as their low porosity and permeability limit prevent radionuclide migration (Figure 1.1 (b)) (Chan et al., 2001; Houben et al., 2013; Blanco-Martín et al., 2015). This combination of energy storage and waste isolation capabilities highlights the strategic importance of salt formations in supporting both energy security and environmental sustainability (Winterle et al., 2012).

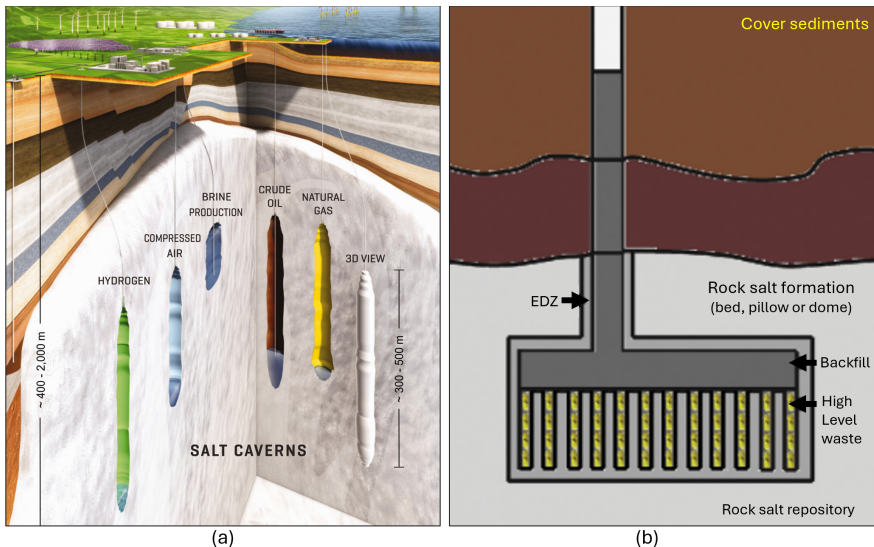


Figure 1.1 (a) Salt caverns used for various liquid and gas energy storage applications (source: <http://www.kbbnet.de/en/>); (b) A sealed radioactive waste repository in rock salt, with cavities and boreholes surrounded by an excavation damaged zone (EDZ) (adapted from Houben et al., 2013).

Salt caverns are typically developed in salt diapirs or domes, where thick salt layers have migrated upward through overlying rock due to buoyant forces acting over geological time (Figure 1.1 (a)). These structures offer ideal conditions for cavern construction because of the homogeneity and low permeability of salt. Salt caverns are usually created at depths down to 2000 m, where the geostatic pressure ensures the mechanical stability and tightness of the surrounding salt. Typical salt cavern dimensions include heights of 300 to 500 m, diameters of 50 to 100 m, and total volumes of up to 500,000 m³. These caverns are often designed for long-term operation, with service lifespans extending over several decades (Michalski et al., 2017; Muhammed et al., 2022). Maintaining cavern integrity and tightness throughout their lifetime is essential for its safe operation. Globally, the lifetime of a storage cavern consists of the following phases:

- 1) **Exploration:** The general potential for constructing a salt cavern is assessed using geological and geophysical tools (Figure 1.2 (a)).
- 2) **Drilling:** In this phase, a well is drilled down to the salt formation to initiate cavern construction. As drilling progresses, a damaged zone forms around the borehole due to changes in in-situ stress conditions (Figure 1.2 (b)). This zone is then exposed to either saturated brine-based mud or oil-based mud.
- 3) **Leaching:** In the controlled solution mining process, water is injected to dissolve the salt, while brine is simultaneously extracted, gradually creating a subsurface cavity. (Figure 1.2 (c)). A blanket of oil or nitrogen is typically used to control the shape and stability of the cavity during leaching. The duration of the leaching process varies depending on the cavern size, leaching method, and geological conditions, typically ranging from several months to several years (Chromik & Korzeniowski, 2021). Existing fractures may become exposed to the undersaturated brine, potentially causing dissolution along fracture surfaces.
- 4) **Gas fill:** The injection of gas marks the beginning of the operational phase ((Figure 1.2 (d)) of the storage facility. The upper damaged zone is in contact with gas under relatively dry conditions, while the lower damaged zone remains in contact with brine.
- 5) **Storage:** The cavern is typically isolated from surface facilities, except during withdrawal or injection of the stored material ((Figure 1.2 (e)). For nuclear waste disposal in rock salt repositories, engineered backfill materials (primarily compacted crushed salt) are used to isolate the waste and ensure long-term containment under effectively dry environment, although minor brine inclusions may still exist over long timescales.
- 6) **Rebrining:** The existing storage medium is displaced and substituted with brine within the cavern. This process may be necessary before interventions (i.e., maintenance, inspection, or equipment replacement), changing the storage medium, or cavern abandonment ((Figure 1.2 (f)).
- 7) **Abandonment:** Permanently sealing the cavern, which is filled with saturated brine. The damage zone will be subjected to saturated brine for an extended period (Kroon et al., 2003; Bérest et al., 2001a) ((Figure 1.2 (g)).

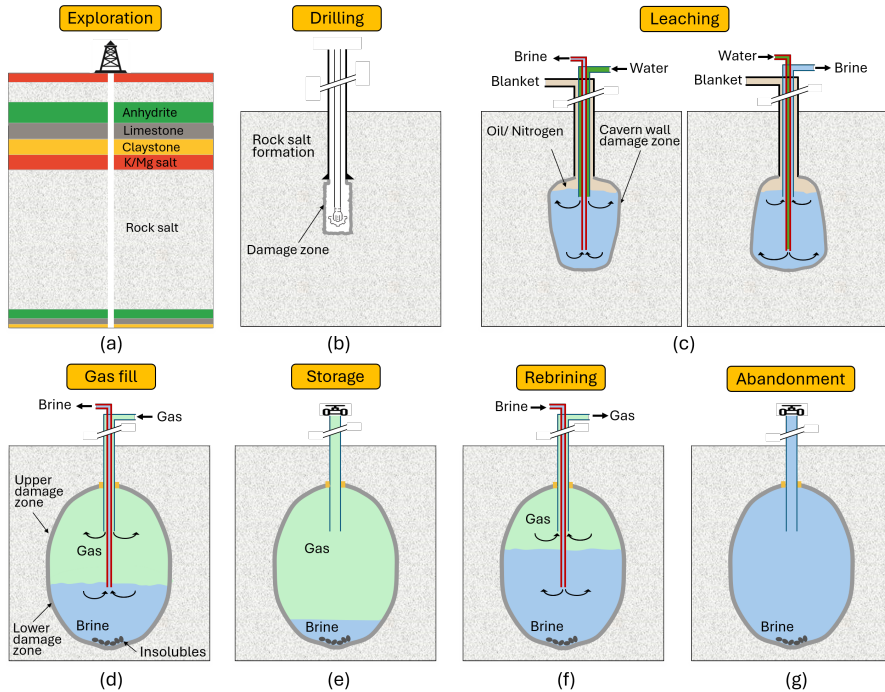


Figure 1.2. Schematic illustration of the main operational life cycle phases of a storage cavern (adapted from Groenenberg et al., 2020; Buzogany et al., 2024). (a) Geological exploration; (b) Drilling into the salt formation; (c) Leaching phase: left shows direct circulation (water injected from the top enlarges the upper part of the cavern), right shows reverse circulation (water injected from the bottom enlarges the lower part); (d) Gas injection and brine withdrawal; (e) Storage phase with the cavern sealed from surface facilities; (f) Rebrining phase where brine is injected to displace and extract stored gas; (g) Abandonment phase during which the cavern is filled with saturated brine.

From the initial drilling and controlled solution mining through the operational phase to eventual abandonment (Figure 1.2 (b)-(g)), the salt surrounding the entire cavern, including regions near the wellbore and along the cavern walls, may undergo mechanical, hydraulic, and geochemical changes, leading to stress redistribution that may initiate and propagate fractures on the short and long term. These processes may eventually result in the development of a narrow, permeable zone known as the damaged or disturbed zone (Houben et al., 2013; Groenenberg et al., 2020).

Specifically, fracture formation varies across the cavern's life cycle. During the leaching phase, factors contributing to fracture formation are the imbalance between the internal fluid pressure within the developing cavern and the surrounding geostatic stress field (Tsang et al., 2005; Houben et al., 2013). In the subsequent operational phase, cyclic pressure fluctuations caused by repeated injection and withdrawal of gas or fluid can further aggravate the damage. Salt near the cavern wall is particularly susceptible to shear failure under deviatoric stress conditions, leading to the progressive accumulation of microdamage (Zhang et al., 2023). At the microscale, this manifests as the

development of microfractures within the damage zone, resulting in mechanical softening, increased permeability, and volumetric expansion (Lüdeling et al., 2015). Fractures within the damage zone, along with pre-existing faults in rock salt can act as high-conductivity flow paths (from 10^{-16} m² to 10^{-20} m²), i.e., with transmissivity orders of magnitude greater than that of intact rock ($< 10^{-20}$ m²) (Yasuhara, 2004; Elkhoury et al., 2015). Thus, salt fractures can act as potential pathways for fluid or gas migration as well as zones of mechanical weakness (Leijon, 1993; Bérest et al., 2001b), thereby posing risks to the integrity and sealing performance of salt caverns.

However, rock salt fractures have been shown to close over time under elevated temperature and normal stress (Li et al., 2024), resulting in reduced aperture, decreased permeability (sealing behaviour), and restored mechanical strength (healing behaviour) (Chan et al., 1998; Donadio, 2017). The sealing and healing processes of rock salt fractures in the damage zone are critical for preventing leakage and maintaining structural integrity. Therefore, a thorough understanding of the associated changes in the physical and mechanical properties of rock salt fractures, along with the underlying mechanisms, is essential to ensure the long-term safety and reliability of underground storage systems.

1.1 Motivation

Fractures in the damage zone of a salt cavern are typically exposed to undersaturated brine during the leaching phase (Figure 1.2 (c)). This exposure allows the brine to penetrate the fracture network, which will enhance dissolution. The injection of fresh water, combined with the simultaneous withdrawal of brine, further promotes dissolution. This process is referred to as open system dissolution, characterized by a continuous source and sink mechanism. In contrast, during the operation and abandonment phases, fractures are generally in contact with saturated brine (Figure 1.2 (d)-(f)). Additionally, rock salt fractures may be exposed to oil/ nitrogen during leaching to prevent excessive dissolution to cavern roof, and to gas during storage operations, both of which present relatively dry conditions.

The geometrical and mechanical evolution of fractures is generally governed by the interplay among the initial fracture geometry, fluid composition, normal stress, and loading duration, resulting in a complex hydro-mechanical-chemical process (Fuenkajorn & Phueakphum, 2011; Ji et al., 2022; Zeng et al., 2024). Given the high solubility of salt, the chemical component of the fluid-rock interaction plays an even more critical role than in less soluble materials. As shown in Figure 1.3 (b)-(c), during the leaching process, undersaturated brine may flow into and through salt fractures, which would initiate dissolution and transport of the dissolved salt along the fracture, thereby changing the fracture geometry, increasing the salt concentration, and enhancing the fracture permeability. The evolution of fracture geometry depends on both the fluid flow rate and concentration. In this context, geometry is used as an umbrella term that includes fracture aperture as well as the number and shape of asperities along the fracture walls. In turn, variations in fracture geometry affect fluid flow over time, leading to localized changes in dissolution and transport rates (Deng & Spycher, 2019; Zhou et al., 2022).

During the operation and abandonment phases (Figure 1.3 (d)–(f)), salt fractures may be exposed to either dry conditions or saturated brine. Time-dependent compaction can alter fracture morphology and reduce aperture, leading to decreased permeability (i.e., sealing). Furthermore, when opposing fracture surfaces come into contact at local asperities, mechanical recovery of fractures may occur (i.e., healing). Experimentally, mechanical recovery is shown to increase monotonically and continuously with healing time (Fuenkajorn & Phueakphum, 2011; Li et al., 2024). Specially, when a thin film of saturated brine is present on grain surfaces, rapid deformation at the grain scale may occur, which would accelerate both sealing and healing. Previous studies have primarily focused on the grain scale or centimetre scale of rock salt, often neglecting the role of fracture surface geometry (Deng & Spycher, 2019; Zhou et al., 2022; Li et al., 2024). Consequently, the quantitative relationship between the evolution of the physical and mechanical properties of rock salt fractures and changes in fracture surface geometry remains poorly understood.

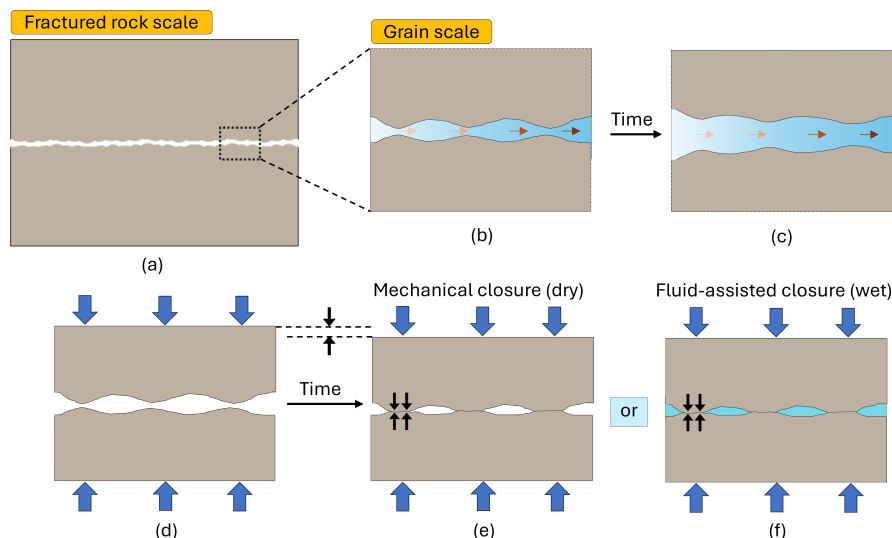


Figure 1.3. (a) Original fracture within the damage zone. (b)–(c) Dissolution of rock salt at the grain scale during the leaching process, where undersaturated brine induces dissolution, followed by transport of dissolved salt along the fracture, leading to increased aperture and salt concentration along the flow path. (d)–(f) Progressive fracture closure over time: (e) due to mechanical compaction; (f) due to solution-assisted healing, with brine inclusions indicated in blue within the fracture.

1.2 Fluid-rock interactions in rock salt fractures

1.2.1 Dissolution and transport versus sealing processes

In open systems, dissolved species are transported downstream, where ultimately, under the influence of distance, pressure and temperature, local supersaturation may occur, which would result in precipitation. Previous studies have examined the influence

INTRODUCTION

of fracture geometry on permeability in open systems, where continuous fluid flow enables mass exchange with the surroundings (Weisbrod et al., 2012; Noiriél & Deng, 2018; Deng & Spycher, 2019; Ling et al., 2023). In contrast, closed systems allow no external exchange, and solute redistribution is governed entirely by local conditions (Simon, 1981; Yu et al., 2018). In both open and closed systems, solute dissolution and transport are governed by the combined effects of advection, diffusion, and chemical reactions. Advection describes the transport of solutes by bulk fluid flow, while diffusion refers to molecular movement driven by concentration gradients. Chemical reactions, such as dissolution and precipitation, modify both the fluid composition and the fracture surfaces. Consequently, the evolution of permeability and fracture geometry during dissolution results from the dynamic interaction of these processes, which all operate on a process-specific time and length scale within the fracture network.

To study dissolution and transport processes in fracture networks at the micro-scale microfluidic networks are either fabricated from polymethyl methacrylate (PMMA) chips or simulated in Hele-Shaw cells. These methods enable direct visualization of both dissolution and precipitation phenomena within the network (Wang et al., 2022; Zhou et al., 2022). As shown in see Figure 1.4 (a), pore-scale experiments (< cm) demonstrate that the dissolution behaviour within fracture channels can be classified into three main regimes: compact, wormhole (including conical, dominant, and ramified types), and uniform, based on the Péclet number (Pe) and Damköhler number (Da) (Figure 1.4 (b)). At the pore scale or within centimetre-scale fractures, the transverse Péclet number compares the advective transport rate along the fracture to the diffusive transport rate across the fracture walls. The Damköhler number represents the ratio between the chemical reaction rate and the diffusive mass transfer rate, as shown in Eqs. (1.1) and (1.2).

$$Pe = \bar{v}a/D_m \quad (1.1)$$

where $\bar{v}$ is the average fluid velocity ($\text{m}\cdot\text{s}^{-1}$), D_m is the molecular diffusion ($\text{m}^2\cdot\text{s}^{-1}$) and a is the fracture aperture (m).

$$Da = K_r L^{*2}/D_m \quad (1.2)$$

where K_r is a first-order kinetic rate constant (s^{-1}), and L^* is a characteristic length (m).

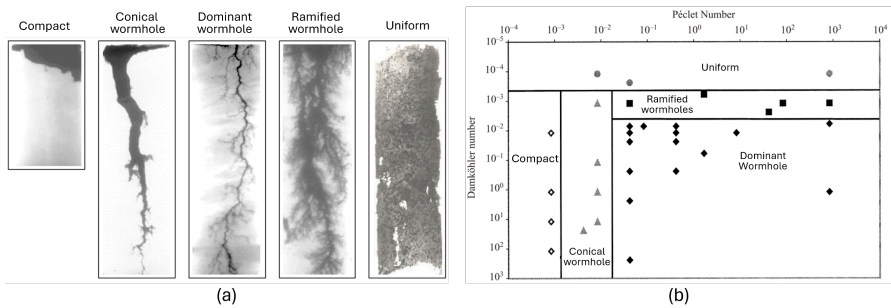


Figure 1.4. (a) Dissolution patterns in fractured rock (Fredd et al., 2000); (b) Dissolution regimes in Péclet number - Damköhler number space (adapted from Golfier et al., 2002)

At low Damköhler (Da) values, transport rates significantly exceed reaction rates, creating a reaction-limited system that leads to uniform fracture dissolution (top in Figure 1.4 (b)). This happens because the reactive species distribute homogeneously throughout the pore network or fracture channel due to rapid fluid transport, leading to consistent dissolution patterns across the medium. At high Da values, reaction rates exceed transport rates, creating a transport-limited system that produces localized dissolution. In this regime, reactive species are quickly consumed near the inlet, generating compact dissolution patterns with intense local alterations (left in Figure 1.4 (b)). At intermediate Da values, where reaction and transport rates reach comparable magnitudes, fracture channelization becomes dominant (centre in Figure 1.4 (b)). These conditions promote the formation of preferential flow paths, or wormholes, that extend through the fracture space along the primary flow direction. The channel development follows a self-reinforcing process: initial dissolution heterogeneities create local permeability increases, which concentrate flow and enhance dissolution along these preferential pathways. The resulting evolution of fracture geometry is closely coupled to local variations in reaction and transport rates, both of which are strongly governed by the initial surface morphology (Rong et al., 2020).

To go from fabricated and simplified channels in analogue materials, flow-through experiments are conducted on rock samples at both millimetre and centimetre scales. The visualization of dissolution pattern evolution in rock fractures across these scales is achieved using a combination of imaging and analytical techniques. This can be achieved in 2D by using camera imaging to monitor the evolution of rock salt fracture walls during dissolution. Observations show that dissolution patterns shift from a wedge-shaped pattern to a uniform pattern with increasing flow rate (Zhou et al., 2022). In three-dimensional studies, nuclear magnetic resonance (NMR) imaging has been used to investigate flow and dissolution patterns in rough-walled, water-saturated halite fractures. Results show that the spatial correlations between dissolution patterns, fracture morphology, flow distribution, and the mineralogical composition of the rock matrix are governed by the overall Damköhler number (Dijk et al., 2002). In addition, micro-computed tomography (micro-CT) has been applied to observe dissolution patterns in halite samples subjected to undersaturated brine injection. These experiments reveal that preferential dissolution pathways develop in regions offering minimal resistance to flow, such as large pore networks and pre-existing fractures. Channel formation is found to occur only above a critical flow rate of 0.01 mL/min, while flow rates below this threshold led to a slowly advancing dissolution front. Salt re-precipitation causes clogging and the eventual cessation of flow within certain salt cores (Weisbrod et al., 2012). For the investigation of sealing behaviour of rock salt fractures, microtomography-based observations have been used to investigate the evolution of microfracture networks in damaged natural salt, with a focus on their response to brine-assisted processes (Ji et al., 2022). This observation reveals that rock salt fractures become crystallographically faceted, necked, discontinuous, and disconnected, resulting in increased tortuosity and decreased connectivity within the fracture network (Bos et al., 2000). The non-destructive methods mentioned above enable detailed analysis of flow path evolution during dissolution and fracture morphology evolution. Furthermore, changes in fracture permeability can be estimated by analysing morphological evolution, either through surface geometry data obtained from imaging or from pressure differences along the fracture space (Lyu et al., 2022).

However, these experiments, whether conducted at the pore scale using micro-chips, which poorly represent realistic fracture lengths, or at the centimetre scale, often exhibit low repeatability. Consequently, the role of fracture geometry in rock salt in controlling the development of dissolution patterns, whether advection or diffusion dominated, remains poorly understood at the decimetre scale. This scale captures more realistic fracture lengths compared with those observed in field conditions.

1.2.2 Evolution of mechanical properties of fractures

Fracture and fault healing in rock salt geological systems occurs when fractures become inactive, such as during interseismic periods. The healing process is widely studied in relation to rock friction and the frictional properties of earthquake faults (Marone, 1998). Fault friction experiments are typically conducted on simulated fault gouges placed between various types of forcing blocks. These include: (1) the saw-cut setup; (2) the double-direct shear setup; (3) direct-shear set-up and (4) the ring shear setup (Niemeijer et al., 2019). Frictional healing is typically evidenced by an increase in static friction during quasi-stationary contact. Most studies have found that frictional healing exhibits a log-linear relationship with hold time (Dieterich, 1972; Dieterich, 1994; Marone, 1998). While effective fracture healing can occur in various rock types, most rocks found in the upper crust, such as sandstone, limestone, and clay, typically require substantially higher temperatures, greater pressures, and significantly longer time periods to heal compared to rock salt (Niemeijer et al., 2022; Brantut et al., 2015; Alneasan et al., 2022). The relatively rapid healing behaviour of rock salt was further explored through rotary shear experiments using salt granular gouge to examine the effects of wall rock surface roughness on frictional behaviour (Bos et al., (2000)). The coefficients of friction are roughly similar in the wet smooth, dry rough, and wet rough surface experiments, while the coefficient of friction in the dry smooth surface experiment is lower (Figure 1.5 (a)). Additionally, microscopic inspection of wet-deformed halite fault gouges reveals truncation, indentation, interpenetration, and overgrowth microstructures, all characteristic of pressure solution. However, the use of gouge material in experiments limits the ability to obtain detailed information on the evolution of rock salt fracture roughness. In addition to experiments using gouge material, the healing behaviour of fractured rock salt at the centimetre scale has been investigated through Brazilian splitting tests (Li et al., 2024), unconfined compressive strength (UCS) test (Fuenkajorn & Phueakphum, 2011), and direct shear box tests (Salzer et al., 2007). In Salzer's study, an increase in the cohesion of rock salt fractures was observed after healing, as interpreted using the Mohr-Coulomb criterion (Figure 1.5 (b)). Overall, the strength recovery of rock salt fractures is time-dependent and influenced by the presence of fluid, applied normal stress, and temperature (Costin & Wewersik., 1980; Brodsky & Munson., 1994).

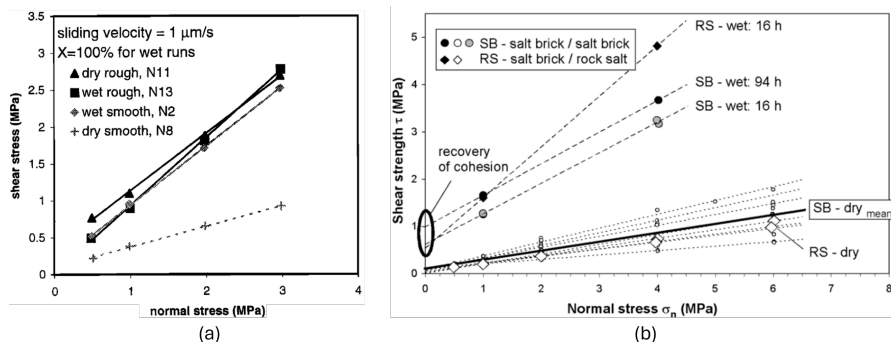


Figure 1.5. (a) Shear stress versus normal stress data for dry and wet gouge samples in contact with smooth and rough wall rock surface are presented within the Mohr-Coulomb criterion framework (cited from Bos et al., 2000); (b) Shear strength characteristics of lab-dry and moistened brick-brick and brick-rock salt contacts. Cohesion recovery (i.e., healing) is promoted by the presence of moisture and increase systematically with stationary ageing over 16, 70 and 94 hours (cited from Salzer et al., 2007).

An important factor influencing the healing process is the presence of pore fluid. A saturated solution occupying the space between granular fault gouge or rock surfaces can significantly promote healing. Tensile strength tests conducted on rock salt samples approximately 1 cm in size have shown that elevated temperature, increased humidity, and higher normal stress all contribute to enhanced healing (Li et al., 2024). Additionally, rapid crystal growth on centimetre-scale rock salt fractures has been observed, with crystals growing until they bridged the fracture, causing segmentation along its length and contributing to strength recovery. The effects of fracture type, including tension-induced fractures, saw-cut fractures, and smooth polished fractures, on the healing of cylindrical rock salt sample with a diameter of 2.5 cm and a length of 5 cm have also been studied (Fuenkajorn & Phueakphum, 2011). Their study shows that the healing behaviour of salt fractures largely depends on their origin. Fractures formed by the separation or splitting of salt crystals tend to heal relatively easily, even under low stress and within a short period. However, a quantitative relationship between fracture surface roughness and healing behaviour in rock salt has not yet been established, and the long-term healing of rock salt fractures (> 1 week) remains poorly understood. Additionally, it remains unclear whether the healing process follows a log-linear relationship, as observed in the frictional healing behaviour of gouge materials.

1.2.3 Micro-mechanisms active in salt deformation

From experimental and microstructural observations, it has been shown that rock salt deformation involves a range of mechanisms that vary with temperature and deviatoric stress conditions (Figure 1.6). Each mechanism leaves distinct microstructural signatures. Under high differential stress conditions, brittle failure and cataclasis occur and are typically characterized by grain fracturing, angular fragments, and localized zones of intense strain (see top in Figure 1.6). At intermediate stress and high temperature, rock deformation is dominated by dislocation activity, including both glide and climb

mechanisms (see top-right in Figure 1.6). Carter et al., (1993) and Hansen (1987) observed that dislocation glide along specific crystallographic planes produces sharp, linear etch pit patterns, which serve as indicators of the active slip systems. In contrast, dislocation climb is typically associated with the development of subgrains and a reduced density of free dislocations, while cross-slip of screw dislocations results in higher dislocation densities and wavy slip bands. Under low differential stress and low temperature, deformation is governed by pressure-solution processes, characterized by microstructural features such as indentations, truncations, overgrowths, and pressure shadows (see left-bottom in Figure 1.6). This mechanism is governed by Fick's law, where a stress-induced chemical potential gradient drives mass transfer from highly stressed to less stressed regions (Spiers et al., 1990). In long term conditions, rock salt deformation is dominated by dislocation creep mechanisms, particularly through cross slip and climb processes. The presence of brine significantly alters this behaviour by introducing additional mechanisms such as fluid enhanced dynamic recrystallization. Additionally, thermodynamic models have been effectively used to describe rock salt deformation during compaction creep experiments. These models provide a framework for understanding energy-driven processes such as phase transitions, chemical reactions, and dissolution–precipitation, while remaining consistent with fundamental principles of energy conservation (Spiers et al., 1990; Urai et al., 2008).

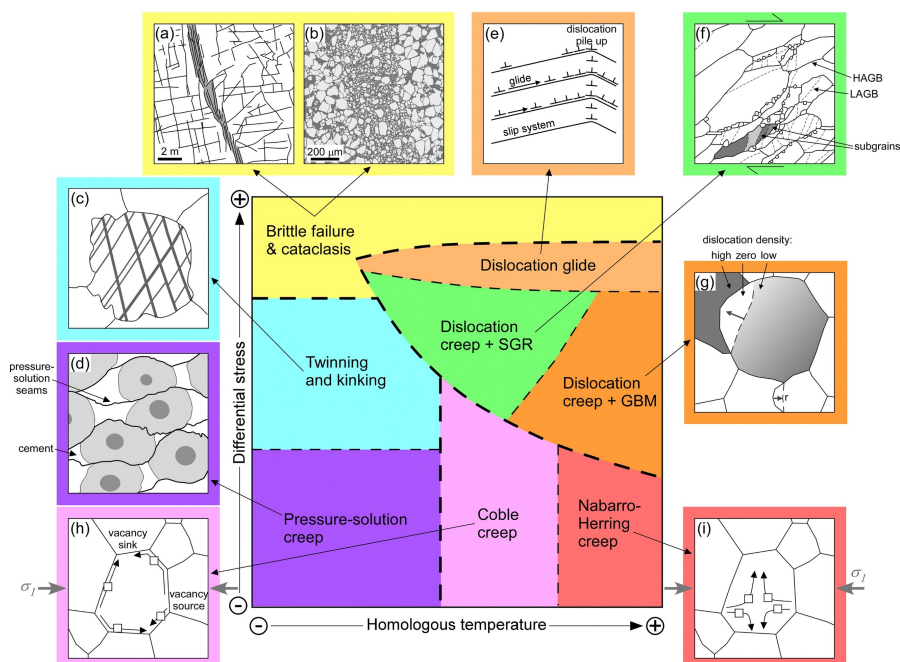


Figure 1.6. Idealized deformation mechanism map at the space of differential stress and homologous temperature (i.e., normalised to the mineral's melting point) (Gomez-Rivas et al., 2020).

However, conventional deformation mechanism maps describe the behaviour of intact, continuous rock as a solid medium and do not consider the presence of fractures. In fractured rock, mechanical closure alone is often insufficient. When fracture closure is driven solely by stress induced compaction, a gradual increase in fluid pressure can easily reopen previously closed fractures. In contrast, chemical processes are more effective for achieving permanent fracture sealing and healing through mass transfer. It has been shown that in fractures, pressure solution creep contributes to closure and permeability reduction through the sequence of dissolution at contact asperities, subsequent diffusion along interfaces, and finally precipitation at free surfaces (Yasuhara, 2004). An additional complexity arises from the surface characteristics of fractures, particularly their roughness, which affects the contact area and healing efficiency. Thus, quantifying and characterizing the fracture surface is essential for understanding the healing process.

1.3 Numerical methods and platforms

Laboratory experiments on fluid flow and dissolution in rock salt fractures make it difficult to directly measure parameters such as fluid velocity and concentration distribution along the fracture length. Platforms such as COMSOL Multiphysics have been used to represent dissolution in both fractures and porous media, with meshes that adapt to steep gradients and moving boundaries while coupling fluid flow with reactive transport. These models resolve feedback between dissolution and hydraulics and can explain the time dependent evolution of flow paths, aperture, and permeability (Zhang et al., 2022; Ling et al., 2023).

For the healing behaviour of rock salt fractures, numerical simulations offer a valuable tool to predict long-term strength recovery over years to decades, a timescale that is difficult to capture experimentally. In many studies, fractures (i.e., discontinuities) are either not explicitly represented or their healing is neglected (Heusermann et al., 2003; Hou et al., 2003; Honório et al., 2024). Interface elements are widely employed to analyse rock fractures, as they accommodate complex geometries and provide high spatial resolution of localised processes. The cohesive zone method (CZM) has been introduced to simulate fracture initiation and propagation, offering efficient representation of complex interface behaviour through flexible traction–separation laws without requiring remeshing (Dugdale, 1960; Barenblatt, 1962). Caballero et al. (2008) proposed an elasto-plastic cohesive zone model with a hyperbolic yield surface that activates fracture under combined compression–shear loading. The formulation accounts for the dependence of shear response on normal stress and reproduces the residual shear-stress plateau observed after peak strength. Healing has been incorporated into CZMs through several strategies. Schimmel and Remmers (2006) partitioned interface stiffness into damaged and undamaged components, allowing the damaged part to recover via a healing function. Alsheghri and Abu Al-Rub (2015, 2016) introduced a thermodynamically consistent CZHM that uses internal variables to restore stiffness and strength as a function of time, temperature, and stress. Freeman et al. (2020) developed a damage–healing CZM with a healing function that varies in both space and time.

Despite these advances, most existing models lack detailed representations of time-dependent healing in rock salt fractures, and validation remains challenging due to the scarcity of experimental data. Additional difficulties include modelling displacement discontinuities and tracking evolving mechanical properties of interface elements/fractures. To address these challenges, interface-based models are increasingly used, not only to reproduce laboratory observations but also to predict the long-term mechanical evolution of rock salt fractures.

1.4 Objectives and outline

This thesis focuses on how the physical and mechanical properties of rock salt fractures evolve over different stages in the lifespan of a salt cavern, with an emphasis on linking fracture geometry to the underlying mechanisms of dissolution and healing. Building on the challenges and knowledge gaps outlined above, the thesis is structured around four main objectives:

- 1) How do variations in salt concentration, flow rate and initial fracture geometry influence the evolution of rock salt fracture geometry in open systems? (Chapter 2)
- 2) To what extent does the presence of a saturated solution promote rock salt fracture healing and what are the dominant mechanisms governing this process? (Chapter 3)
- 3) What is the relationship between healing time, fracture surface roughness, and the recovery of mechanical strength in healed rock salt fractures? (Chapter 3 and 4)
- 4) How can fluid flow velocity and concentration distribution be effectively captured by coupling fluid flow with dissolution processes in COMSOL, and how can healing behaviour of rock salt fractures be incorporated into the interface constitutive model? (Chapter 2 and 5).

This thesis presents an experimental setup developed to investigate the influence of fluid-rock interactions on the evolution of fracture geometry and mechanical properties in rock salt fractures. Complementary numerical simulations are performed to reproduce laboratory conditions, capturing fluid flow velocity and concentration profiles during dissolution, and evaluate the influence of loading duration on the healing behaviour of rock salt fractures. The structure of the thesis is outlined in the following chapters:

Chapter 1: Introduction to thesis topic.

Chapter 2: Visualization and quantification of dissolution process in rock salt channels.

This chapter aims to shed light on how salt concentration and flow rates affect the evolution of fracture geometry and permeability on relatively large laboratory sample scales of 20 cm. We design a novel setup with simplified rectangular channels in salt rocks topped by a glass plate, to perform flow-through experiments. Undersaturated solutions of different concentrations are injected through the model fracture at three different flow rates. The fracture geometry is tracked using a camera. The dissolution rate is measured using an electrical conductivity probe, while the local dissolution mass is determined by the change in volume calculated from the micro-CT results. Additionally,

a coupled reactive transport model developed using COMSOL Multiphysics is employed to analyse fluid velocity distribution and injection salt concentration.

Chapter 3: Investigation into recovery and roughness evolution in rock salt fractures.

We investigate the long-term shear strength recovery of artificial fractures in natural rock salt using direct shear box tests. The results are analysed in terms of mechanical recovery, static and dynamic friction related to stick-slip behaviour and surface microstructure evolution. The effects of healing time and saturated brine on the shear strength recovery, friction behaviour and surface geometry evolution of rock salt fractures, as well as the healing mechanisms under dry and wet conditions, are discussed.

Chapter 4: Healing behaviour of rock salt fracture with varying surface roughness.

The same experimental method is used as in the previous chapter. However, the focus here is how different initial surface roughness and healing conditions affect the mechanical recovery of artificial fractures in natural rock salt.

Chapter 5: Analysis of rock salt healing within a cohesive zone modelling framework.

In this chapter, the elastoplastic constitutive law proposed by Caballero et al. (2008) is introduced to account for the time dependent effects of healing. The law is formulated in terms of normal and shear stresses on the fracture plane and the associated relative displacements. Fracture initiation is described by a hyperbolic yield surface, governed by an internal variable that represents the dissipated fracturing (plastic) work. Progressive degradation of the interface leads to reductions in tensile strength, cohesion, and friction coefficient. The constitutive law is first verified through single element tests under pure tension, pure shear, and combined compression shear loading, and subsequently validated against non-healed dry and wet samples. Healing is considered by introducing an external variable defined in log-linear form with respect to healing time, which results in an expansion of the initial yield surface as the mechanical properties recover. Validation against healed dry and wet samples further demonstrates the model's ability to reproduce shear strength recovery. Finally, long-term simulations spanning years to decades are conducted to assess fracture behaviour at extended timescales.

Chapter 6: Conclusions and recommendations are drawn based on the findings.

Appendix: This section includes additional formulations, figures, and images related to both the experimental and numerical work. Links to the datasets hosted on the 4TU ResearchData repository are also provided. These datasets contain raw images and geometry file from micro-CT, MATLAB scripts for image and data processing.

Declaration of AI usage in this dissertation: The PhD candidate used ChatGPT 4 and 5 to refine the language and context, and to assist in correcting code for image processing and finite element modelling.

1.5 References

- Alneasan, M. and Alzo'ubi, A.K., 2022. Comprehensive investigation of rock fracture behaviour in clay-rich rocks under the effect of temperature: Experimental study under three loading modes (I, I/II, II). *Engineering Fracture Mechanics*, 276, p.108933. <https://doi.org/10.1016/j.engfracmech.2022.108933>
- Alisheghri, A. A., & Abu Al-Rub, R. K. 2016. Finite element implementation and application of a cohesive zone damage-healing model for self-healing materials. *Engineering Fracture Mechanics*, 163, 1–22. <https://doi.org/10.1016/j.engfracmech.2016.06.010>
- Alisheghri, A.A. and Al-Rub, R.K.A., 2015. Thermodynamic-based cohesive zone healing model for self-healing materials. *Mechanics Research Communications*, 70, pp.102-113. <https://doi.org/10.1016/j.mechrescom.2015.10.003>
- Barenblatt, G.I., 1962. The mathematical theory of equilibrium cracks in brittle fracture. *Advances in applied mechanics*, 7, pp.55-129. [https://doi.org/10.1016/S0065-2156\(08\)70121-2](https://doi.org/10.1016/S0065-2156(08)70121-2)
- Bérest, P. and Brouard, B., 2003. Safety of salt caverns used for underground storage blow out; mechanical instability; seepage; cavern abandonment. *Oil & Gas Science and Technology*, 58(3), pp.361-384. <https://doi.org/10.2516/ogst:2003023>
- Bérest, P., Bergues, J., Brouard, B., Durup, J.G. and Guerber, B., 2001a. A salt cavern abandonment test. *International Journal of Rock Mechanics and Mining Sciences*, 38(3), pp.357-368. [https://doi.org/10.1016/S1365-1609\(01\)00004-1](https://doi.org/10.1016/S1365-1609(01)00004-1)
- Bérest, P., Brouard, B. and Durup, J.G., 2001b. Tightness tests in salt-cavern wells. *Oil & Gas Science and Technology*, 56(5), pp.451-469. <https://doi.org/10.2516/ogst:2001037>
- Blanco-Martin, L., Rouabhi, A., Hadij-Hassen, F., Jaworowicz, J., Azabou, M., Hévin, G. and Labaune, P., 2024. Creep of rock salt under a large range of deviatoric stresses. *Rock Mechanics and Rock Engineering*, 57(8), pp.6105-6118. <https://doi.org/10.1007/s00603-024-03841-6>
- Bos, B., Peach, C. J., & Spiers, C. J. 2000. Slip behavior of simulated gouge-bearing faults under conditions favoring pressure solution. *Journal of Geophysical Research: Solid Earth*, 105(B7), 16699–16717. <https://doi.org/10.1029/2000jb900089>
- Brantut, N., 2015. Time-dependent recovery of microcrack damage and seismic wave speeds in deformed limestone. *Journal of Geophysical Research: Solid Earth*, 120(12), pp.8088-8109. <https://doi.org/10.1002/2015JB012324>
- Brodsky, N.S. and Munson, D.E., 1994, June. Thermomechanical damage recovery parameters for rocksalt from the Waste Isolation Pilot Plant. In *ARMA North America Rock Mechanics Symposium* (pp. ARMA-1994). ARMA.
- Buzogany, R. and Bernhardt, H., 2024, November. Hydrogen Storage in Salt Caverns-Current Status and Potential Future Research Topics. In *Fifth EAGE Global Energy Transition Conference & Exhibition (GET 2024)* (Vol. 2024, No. 1, pp. 1-4). European Association of Geoscientists & Engineers. <https://doi.org/10.3997/2214-4609.202421250>
- Caballero, A., Willam, K. J., & Carol, I. 2008. Consistent tangent formulation for 3D interface modeling of cracking/fracture in quasi-brittle materials. *Computer Methods in Applied Mechanics and Engineering*, 197(33–40), 2804–2822. <https://doi.org/10.1016/j.cma.2008.01.011>
- Carter, N.L., Horsman, S.T., Russell, J.E. and Handin, J., 1993. Rheology of rocksalt. *Journal of Structural Geology*, 15(9-10), pp.1257-1271. [https://doi.org/10.1016/0191-8141\(93\)90168-A](https://doi.org/10.1016/0191-8141(93)90168-A)
- Chan, K. S., Bodner, S. R., & Munson, D. E., 2001. Permeability of WIPP salt during damage evolution and healing. *International Journal of Damage Mechanics*, 10(4), 347–375. <https://doi.org/10.1106/H3UV-1URA-AFUY-FX49>
- Chan, K.S., Bodner, S.R. and Munson, D.E., 1998. Recovery and healing of damage in WIPP salt. *International Journal of Damage Mechanics*, 7(2), pp.143-166. <https://doi.org/10.1177/105678959800700204>
- Chromik, M., & Korzeniowski, W. 2021. A method to increase the leaching progress of salt caverns with the use of the hydro-jet technique. *Energies*, 14(18). <https://doi.org/10.3390/en14185833>
- Costin, L.S. and Wawersik, W.R., 1980. Creep healing of fractures in rock salt (No. SAND-80-0392). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States). <https://doi.org/10.2172/5021049>
- Deng, H., & Spycher, N. 2019. Modeling reactive transport processes in fractures. *Reviews in Mineralogy and Geochemistry*, 85(1), 49–74. <https://doi.org/10.2138/rmg.2019.85.3>
- Dieterich, J. H., 1972. Time-dependent friction in rocks. *Journal of Geophysical Research*, 77(20), 3690–3697. <https://doi.org/10.1029/jb077i020p03690>
- Dieterich, J.H. and Kilgore, B.D., 1994. Direct observation of frictional contacts: New insights for state-dependent properties. *Pure and applied geophysics*, 143, pp.283-302. <https://doi.org/10.1007/BF00874332>
- Dijk, P. E., Berkowitz, B., & Yechieli, Y. 2002. Measurement and analysis of dissolution patterns in rock fractures. *Water Resources Research*, 38(2), 5-1-5-12. <https://doi.org/10.1029/2001wr000246>
- Donadio, V., 2018. Salt rock deformation and evolution: damage development and healing in rock salt (Master's thesis). <https://studenttheses.uu.nl/handle/20.500.12932/29830>
- Dugdale, D.S., 1960. Yielding of steel sheets containing slits. *Journal of the Mechanics and Physics of Solids*, 8(2), pp.100-104. [https://doi.org/10.1016/0022-5096\(60\)90013-2](https://doi.org/10.1016/0022-5096(60)90013-2)
- Elkhoury, J.E., Detwiler, R.L. and Ameli, P., 2015. Can a fractured caprock self-heal? *Earth and Planetary Science Letters*, 417, pp.99-106. <https://doi.org/10.1016/j.epsl.2015.02.010>
- Fredd, C.N. and Miller, M.J., 2000, February. Validation of carbonate matrix stimulation models. In *SPE International Conference and Exhibition on Formation Damage Control* (pp. SPE-58713). SPE. <https://doi.org/10.2118/58713-MS>
- Freeman, B. and Jefferson, A., 2024, May. A 3D coupled finite element model for self-healing quasi-brittle materials. In *Engineering Research Conference 2023* (p. 29). doi.org/10.18573/conf1.c
- Fuenkajorn, K., & Phueakphum, D. 2011. Laboratory assessment of healing of fractures in rock salt. *Bulletin of Engineering Geology and the Environment*, 70(4), 665–672. <https://doi.org/10.1007/s10064-011-0370-y>
- Golfier, F., Zarcone, C., Bazin, B., Lenormand, R., Lasseux, D., & Quintard, M. 2002. On the ability of a Darcy-scale model to capture wormhole formation during the dissolution of a porous medium. *Journal of Fluid Mechanics*, 457, 213–254. <https://doi.org/10.1017/S0022112002007735>
- Gomez-Rivas, E., Butler, R. W. H., Healy, D., & Alsop, I. 2020. From hot to cold - The temperature dependence on rock deformation processes: An introduction. *Journal of Structural Geology*, 132. <https://doi.org/10.1016/j.jsg.2020.103977>
- Groenenberg, R., Koornnef, J., Sijm, J., Janssen, G., Morales-Espana, G., Van Stralen, J., Hernandez-Serna, R., Smekens, K., Juez-Larre, J., Goncalvez, G. and Wasch, L.J., 2020. Large-scale energy storage in salt caverns and depleted fields (Ises)—project findings. TNO 2020 R12006.

- Hansen, F.D., 1987. Physical and mechanical variability of natural rock salt. *Bulletin of the Association of Engineering Geologists*, 24(2), pp.227-234. <https://doi.org/10.2113/gseegeosci.xxiv.2.227>
- He, W., Luo, X., Evans, D., Busby, J., Garvey, S., Parkes, D., & Wang, J. 2017. Exergy storage of compressed air in cavern and cavern volume estimation of the large-scale compressed air energy storage system. *Applied Energy*, 208, 745–757. <https://doi.org/10.1016/j.apenergy.2017.09.074>
- Heusermann, S., Rolfs, O. and Schmidt, U., 2003. Nonlinear finite-element analysis of solution mined storage caverns in rock salt using the LUBBY2 constitutive model. *Computers & structures*, 81(8-11), pp.629-638. [https://doi.org/10.1016/S0045-7949\(02\)00415-7](https://doi.org/10.1016/S0045-7949(02)00415-7)
- Honório, H.T. and Hajibeygi, H., 2024. Three-dimensional multi-physics simulation and sensitivity analysis of cyclic energy storage in salt caverns. *International Journal of Hydrogen Energy*, 94, pp.1389-1405. <https://doi.org/10.1016/j.ijhydene.2024.11.081>
- 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), pp.725-738. [https://doi.org/10.1016/S1365-1609\(03\)00064-9](https://doi.org/10.1016/S1365-1609(03)00064-9)
- Houben, M. E., ten Hove, A., Peach, C. J., & Spiers, C. J. 2013. Crack healing in rocksalt via diffusion in adsorbed aqueous films: Microphysical modelling versus experiments. *Physics and Chemistry of the Earth*, 64, 95–104. <https://doi.org/10.1016/j.pce.2012.10.001>
- Ji, Y., Spiers, C.J., Hangx, S.J.T., de Bresser, J.H.P. and Drury, M.R., 2022. 4D microtomography of brine-assisted healing processes in deformation-damaged rocksalt: A first look. In *The Mechanical Behavior of Salt X* (pp. 88-97). CRC Press. <https://doi.org/10.1201/9781003295808-9>
- King, M., Jain, A., Bhakar, R., Mathur, J., & Wang, J. 2021. Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK. *Renewable and Sustainable Energy Reviews*, 139. <https://doi.org/10.1016/j.rser.2021.110705>
- Kroon, I.C., Orlic, B. and Scheffers, B.C., 2003. Abandonment of Solution Mined Salt Caverns in the Netherlands. Part 2. Best Practises and methods.
- Kruck, O., Crotogino, F., Prelicz, R. and Rudolph, T., 2013. Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe. *KBB Undergr. Technol. GmbH*, pp.1-32.
- Kumar, K.R., Honório, H., Chandra, D., Lesueur, M. and Hajibeygi, H., 2023. Comprehensive review of geomechanics of underground hydrogen storage in depleted reservoirs and salt caverns. *Journal of Energy Storage*, 73, p.108912. <https://doi.org/10.1016/j.est.2023.108912>
- Lehtveer, M., Mattsson, N., & Hedenus, F. 2017. Using resource based slicing to capture the intermittency of variable renewables in energy system models. *Energy Strategy Reviews*, 18, 73–84. <https://doi.org/10.1016/j.esr.2017.09.008>
- Leijon, B., 1993. Mechanical properties of fracture zones (No. SKB-TR--93-19). Swedish Nuclear Fuel and Waste Management Co.
- Li, Z., Kang, Y., Fan, J., Fourmeau, M., Chen, J., Jiang, D., & Nelias, D. 2024. Macroscopic experimental study and microscopic phenomenon analysis of damage self-healing in salt rock. *Engineering Geology*, 338. <https://doi.org/10.1016/j.enggeo.2024.107634>
- Ling, D., Zhu, S., Zheng, J., Xu, Z., Zhao, Y., Chen, L., Shi, X., & Li, J. 2023. A simulation method for the dissolution construction of salt cavern energy storage with the interface angle considered. *Energy*, 263. <https://doi.org/10.1016/j.energy.2022.125792>
- Liu, W., Li, Q., Yang, C., Shi, X., Wan, J., Jurado, M. J., Li, Y., Jiang, D., Chen, J., Qiao, W., Zhang, X., Fan, J., Peng, T., & He, Y. 2023. The role of underground salt caverns for large-scale energy storage: A review and prospects. In *Energy Storage Materials* (Vol. 63). Elsevier B.V. <https://doi.org/10.1016/j.ensm.2023.103045>
- Lord, A.S., 2009. Overview of geologic storage of natural gas with an emphasis on assessing the feasibility of storing hydrogen (No. SAND2009-5878). Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States). <https://doi.org/10.2172/975258>
- Lüdeling, C., Günther, R.M., Knauth, M. and Minkley, W., 2015, June. Healing of Rock Salt Damage and Applications. In *ARMA US Rock Mechanics/Geomechanics Symposium* (pp. ARMA-2015). ARMA.
- Lyu, C., Liu, J., Ren, Y., Liang, C., & Zeng, Y. 2022. Mechanical characteristics and permeability evolution of salt rock under thermal-hydro-mechanical (THM) coupling condition. *Engineering Geology*, 302. <https://doi.org/10.1016/j.enggeo.2022.106633>
- Marone, C., 1998. Laboratory-derived friction laws and their application to seismic faulting. *Annual Review of Earth and Planetary Sciences*, 26(1), pp.643-696. <https://doi.org/10.1146/annurev.earth.26.1.643>
- Mehr, A.S., Phillips, A.D., Brandon, M.P., Pryce, M.T. and Carton, J.G., 2024. Recent challenges and development of technical and technoeconomic aspects for hydrogen storage, insights at different scales; A state of art review. *International Journal of Hydrogen Energy*, 70, pp.786-815. <https://doi.org/10.1016/j.ijhydene.2024.05.182>
- Michalski, J., Bünger, U., Crotogino, F., Donadei, S., Schneider, G. S., Pregger, T., Cao, K. K., & Heide, D. 2017. Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition. *International Journal of Hydrogen Energy*, 42(19), 13427–13443. <https://doi.org/10.1016/j.ijhydene.2017.02.102>
- Muhammed, N.S., Haq, B., Al Shehri, D., Al-Ahmed, A., Rahman, M.M. and Zaman, E., 2022. A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. *Energy Reports*, 8, pp.461-499. <https://doi.org/10.1016/j.egy.2021.12.002>
- Niemeijer, A., Fagereng, A., Ikari, M., Nielsen, S., & Willingshofer, 2019. Faulting in the laboratory. In *Understanding Faults: Detecting, Dating, and Modeling* (pp. 167–220). <https://doi.org/10.1016/B978-0-12-815985-9.00005-9>
- Niemeijer, A.R., Spiers, C.J. and Bos, B., 2002. Compaction creep of quartz sand at 400–600 °C: Experimental evidence for dissolution-controlled pressure solution. *Earth and Planetary Science Letters*, 195(3-4), pp.261-275. [https://doi.org/10.1016/S0012-821X\(01\)00593-3](https://doi.org/10.1016/S0012-821X(01)00593-3)
- Noiriel, C., & Deng, H. 2018. Evolution of planar fractures in limestone: The role of flow rate, mineral heterogeneity and local transport processes. *Chemical Geology*, 497, 100–114. <https://doi.org/10.1016/j.chemgeo.2018.08.026>
- Ozarstan, A. 2012. Large-scale hydrogen energy storage in salt caverns. *International Journal of Hydrogen Energy*, 37(19), 14265–14277. <https://doi.org/10.1016/j.ijhydene.2012.07.111>
- Patanwar, Y.K., Kim, H.M., Deb, D. and Gujjala, Y.K., 2024. Underground storage of hydrogen in lined rock caverns: An overview of key components and hydrogen embrittlement challenges. *International Journal of Hydrogen Energy*, 50, pp.116-133. <https://doi.org/10.1016/j.ijhydene.2023.08.342>

INTRODUCTION

- Rong, G., Tan, J., Zhan, H., He, R., & Zhang, Z. 2020. Quantitative evaluation of fracture geometry influence on nonlinear flow in a single rock fracture. *Journal of Hydrology*, 589. <https://doi.org/10.1016/j.jhydrol.2020.125162>
- Salzer, K., Popp, T., & Böhnel, H., 2017. Mechanical and permeability properties of highly pre-compacted granular-salt bricks. In *The Mechanical Behavior of Salt – Understanding of THMC Processes in Salt* (pp. 239–248).
- Schimmel, E.C. and Remmers, J.J.C., 2006. Development of a constitutive model for self-healing materials. Delft Aerospace Computational Science.
- Simon, B., 1981. Dissolution rates of NaCl and KCl in aqueous solution. *Journal of Crystal Growth*, 52, pp.789-794. [https://doi.org/10.1016/0022-0248\(81\)90377-8](https://doi.org/10.1016/0022-0248(81)90377-8)
- Spiers, C.J., Schutjens, P.M.T.M., Brzesowsky, R.H., Peach, C.J., Liezenberg, J.L. and Zwart, H.J., 1990. Experimental determination of constitutive parameters governing creep of rock salt by pressure solution. *Geological Society, London, Special Publications*, 54(1), pp.215-227. <https://doi.org/10.1144/GSL.SP.1990.054.01.21>
- Tsang, C. F., Bernier, F., & Davies, C. 2005. Geohydromechanical processes in the Excavation Damaged Zone in crystalline rock, rock salt, and indurated and plastic clays—in the context of radioactive waste disposal. *International Journal of Rock Mechanics and Mining Sciences*, 42(1), 109–125. <https://doi.org/10.1016/j.ijrmms.2004.08.003>
- Urai, J.L., Schlöder, Z., Spiers, C.J. and Kukla, P.A., 2008. Flow and transport properties of salt rocks. *Dynamics of complex intracontinental basins: The central European basin system*, pp.277-290.
- Wang, T., Hu, R., Yang, Z., Zhou, C.X., Chen, Y.F. and Zhou, C.B., 2022. Transitions of dissolution patterns in rough fractures. *Water Resources Research*, 58(1), p.e2021WR030456. <https://doi.org/10.1029/2021WR030456>
- Weisbrod, N., Alon-Mordish, C., Konen, E., & Yechieli, Y. 2012. Dynamic dissolution of halite rock during flow of diluted saline solutions. *Geophysical Research Letters*, 39(9). <https://doi.org/10.1029/2012GL051306>
- Williams, J.D., Williamson, J.P., Parkes, D., Evans, D.J., Kirk, K.L., Sunny, N., Hough, E., Vosper, H. and Akhurst, M.C., 2022. Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt cavern storage potential of bedded halite formations. *Journal of Energy Storage*, 53, p.105109. <https://doi.org/10.1016/j.est.2022.105109>
- Winterle, J., Ofogebu, G., Pabalan, R., Manepally, C., Mintz, T., Pearcy, E., Smart, K., McMurry, J., Pauline, R., Antonio, S., & Fedors, R. 2012. *Geologic disposal of high-level radioactive waste in salt formations*. U.S. Nuclear Regulatory Commission Washington.
- Yasuhara, H. 2004. Evolution of permeability in a natural fracture: Significant role of pressure solution. *Journal of Geophysical Research*, 109(B3). <https://doi.org/10.1029/2003jb002663>
- Yu, Y. mei, Liang, W. guo, & Liu, J. shan. 2018. Influence of solution concentration and temperature on the dissolution process and the internal structure of glauberite. *International Journal of Minerals, Metallurgy and Materials*, 25(11), 1246–1255. <https://doi.org/10.1007/s12613-018-1677-5>
- Zeng, Z., Ma, H., Yang, C., Zhao, K., Liang, X., Li, H. and Zheng, Z., 2024. Self-healing behaviors of damaged rock salt under humidity cycling. *International Journal of Rock Mechanics and Mining Sciences*, 174, p.105636. <https://doi.org/10.1016/j.ijrmms.2024.105636>
- Zhang, H., Wang, P., Wanyan, Q., Li, K., Gao, K. and Yue, X., 2023. Sensitivity analysis of operation parameters of the salt cavern under long-term gas injection-production. *Scientific Reports*, 13(1), p.20012. <https://doi.org/10.1038/s41598-023-47352-w>
- Zhang, Q., Deng, H., Dong, Y., Molins, S., Li, X. and Steefel, C., 2022. Investigation of coupled processes in fractures and the bordering matrix via a micro-continuum reactive transport model. *Water Resources Research*, 58(2), p.e2021WR030578. <https://doi.org/10.1029/2021WR030578>
- Zhou, C.X., Hu, R., Li, H.W., Yang, Z. and Chen, Y.F., 2022. Pore-scale visualization and quantification of dissolution in microfluidic rough channels. *Water Resources Research*, 58(11), p.e2022WR032255. <https://doi.org/10.1029/2022WR032255>

2. Visualization and quantification of dissolution and transport process in rock salt fractures

Abstract: *Fractures in caprock or salt domes can be potential escape pathways in storage sites. However, it is unknown how the interplay between rock salt dissolution reaction, solute diffusion, fluid advection, and salt precipitation mechanisms affect fracture morphology. In this study, we develop a custom-designed meso-scale experimental setup, consisting of a rock salt sample with simplified, rectangular fracture channels below a glass plate on top, enabling visualization of fracture geometry evolution as a function of NaCl brine injection at concentrations of 40 or 260 g/L and flow rates of 3 or 9 mL/min. Three different channel geometries are used in the flow-through experiments. Results indicate that: (1) Dissolution is heterogeneous, with greater dissolution near the inlet and at fracture corners. Faster dissolution in convex areas (advection-dominated) compared to concave areas (diffusion-dominated) leads to the progressive smoothing of fracture surfaces, regardless of initial topography. (2) Samples with larger reaction surface area exhibit higher dissolution rates and greater total dissolution mass, though these differences diminish as fluid flow rate and concentration increase. (3) Low salt concentrations and low fluid flow rates promote mass dissolution in the meso-scale model. However, the resulting dissolution patterns do not clearly align with the Péclet (Pe)–Damköhler (Da) framework observed in micro-scale models. This study presents an effective workflow for analysing decimetre-scale dissolution in 3D channels, offering new insights into how fluid conditions and initial fracture geometries influence dissolution rates and the evolution of fracture morphology.*

2.1 Introduction

When rock fractures are exposed to reactive fluid flow, the dissolution of soluble minerals alters surface morphologies, expands apertures, and overall forms dissolution patterns. These patterns, in turn, influence fracture permeability and control the subsequent dissolution rate within fracture networks (Noiriel & Deng, 2018; Deng & Spycher, 2019; Zhou et al., 2022). The evolution of fracture surface morphology and the transition of dissolution patterns is thus governed by the complex interplay among reaction, diffusion, and advection in the flow-dissolution system (Noiriel & Deng, 2018; Deng & Spycher, 2019; Wang et al., 2022; Zhou et al., 2022). Owing to its high solubility, homogeneous composition, ease of sample preparation, rock salt serves as an ideal analogue for investigating fluid–rock interactions. Moreover, rock salt formations have gained recognition as a favourable medium for energy storage. The long-term containment of injected materials depends on the integrity of the salt-based storage system, which requires significant vertical extent, low permeability, and low porosity to prevent fluid migration over time. Salt caverns are typically created through solution mining, a process in which water is injected to dissolve the salt and gradually forms an underground cavity (Figure 2.1 (a)). During the initial leaching process, the surrounding salt near the cavern walls may undergo mechanical, hydraulic, and geochemical changes, leading to stress redistribution that can initiate and propagate fractures. These processes may eventually result in the development of a narrow, permeable zone known as the damaged or disturbed zone around the salt cavern wall. Fractures in this damage zone can create highly conductive flow paths, with permeabilities several orders of magnitude greater than that of intact salt, thereby threatening containment (Figure 2.1 (b)) (Elkhoury et al., 2015; Renshaw et al., 2020). To ensure the long-term safety and effectiveness of storage systems, it is essential to understand how dissolution influences fracture geometry and roughness, and how these changes contribute to increased fracture permeability.

The geometry and permeability of soluble rock fracture is influenced by multiple factors, including mineral composition and spatial distribution (Noiriel & Deng, 2018), confining pressure (Detwiler, 2008), fracture surface roughness, reaction surface and fracture scale (Durham et al., 2001; Zhou et al., 2022; Ladd & Szymczak, 2021). Additionally, salute concentration (Zhou et al., 2022; Detwiler & Rajaram, 2007), injection rate and injection time (Detwiler et al., 2003; Wang et al., 2022), and gravitational effects (Dijk et al., 2002; Detwiler & Rajaram, 2007) also play significant roles. Previous studies have shown that the transition of dissolution patterns in rock fractures under varying solute concentrations and flow rates is commonly characterized by the dimensionless Péclet (Pe) number and Damköhler (Da) number (Kanagawa et al., 2000; Detwiler et al., 2003; Dijk et al., 2002). In homogeneous, soluble porous media or fractured rock, dissolution patterns typically evolve into three distinct types: compact, wormhole, and uniform dissolution (Daccord & Lenormand, 1993; Al-Khulaifi et al., 2018; Wang et al., 2022; Menke et al., 2023). The Pe number represents the ratio of advective transport to diffusive transport, while the Da number quantifies the relative influence of reaction kinetics to advection. A higher Pe indicates that advection dominates over diffusion, meaning solutes are primarily transported by fluid flow rather than diffusive spreading, which is more pronounced at high flow rates. In contrast, a higher Da suggests that reaction kinetics outpace advective transport, leading to rapid chemical reactions that may result

in transport-limited reactions, localized solute depletion, or mineral precipitation (Detwiler et al., 2003; Zhou et al., 2022; Ling et al., 2023).

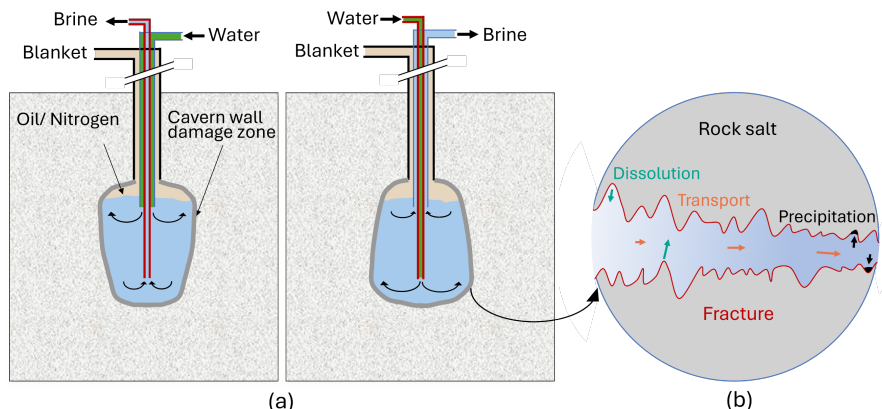


Figure 2.1. (a) Schematic illustration of leaching process: left shows direct circulation (water injected from the top enlarges the upper cavern), right shows reverse circulation (bottom injection promoting lower cavern expansion). (b) During leaching, fractures in the damage zone exposed to undersaturated brine dissolve (green arrows), altering fracture geometry and roughness, and increasing permeability. The dissolved salt can be transported over long distances (orange arrows) and may precipitate at remote locations (black arrows).

In laboratory experiments, microfluidic systems ranging from micrometre to millimetre scale, embedded with geo-materials, are widely used in reactive flow studies. These systems enable real time, pore scale observation of rock fluid-interactions and fluid transport dynamics (Song et al., 2018; Dutka et al., 2020). Dutka et al. (2020) developed micro-visual devices to investigate pore scale reactive transport dynamics in gypsum. Their experiments monitored changes in size and shape of cylindrical gypsum samples (10 mm radius) during dissolution over periods of up to 40 days. They found that a simulation of pore scale flow and transport, using a single surface reaction rate constant, successfully reproduced the observed evolution of sample shape over time. Noiriél & Deng. (2018) conducted flow-through experiments to investigate the evolution of artificial planar fractures in limestone, measuring 15 mm in length and 6 mm in width, when exposed to acidified water at varying flow rates. They observed a transition in the dissolution regime from conical to dominant and ramified wormholes as the flow rate increased. These findings are consistent with previous observations that dissolution follows distinct patterns, progressing from compact to wormhole (channelized) and eventually to uniform dissolution as the flow rate, i.e. Pe number increases. Similarly, Zhou et al. (2022) studied the dissolution behaviour at the pore scale using a soluble, 10 * 10 mm microfluidic chip made out of a single NaCl crystal with rough channels etched inside. Uniform and wedge-shaped dissolution patterns were identified by analysing fracture geometry images in MATLAB under varying salt concentrations and flow rates. At

the millimetre scale, dissolution patterns transition from a wedge-shaped form to a more uniform profile as the flow rate increases from 1×10^{-4} to 0.3 mL/min.

Millimetre- to centimetre-scale fluid injection experiments, combined with high resolution imaging, have been used to investigate the influence of fracture surface evolution on dissolution patterns (Durie et al., 1964; Durie & Jessen., 1964; Weisbrod et al., 2012; Elkhoury et al., 2015). Durie et al. (1964) investigated the effect of surface irregularities on salt dissolution by sealing salt blocks on five sides, exposing a 7 cm × 17 cm face with channels of varying sizes. Under static immersion, they found that larger reactive surfaces, formed by fracture-like features, enhanced the dissolution rate. Subsequently, Durie & Jessen. (1964) carried out flow-through dissolution experiments using rock salt cores (2.5 cm in diameter and 6 cm length) and found that dissolution was primarily controlled by water salinity under laminar flow. However, when turbulence developed at the salt surface, the dissolution rate increased, even when the salinity within the cavity remained constant. This observation aligns with findings from Weisbrod et al. (2012), who conducted injection experiments on cylindrical halite rock cores (8 cm in diameter and 5 cm length) combined with Computer Tomography (CT) analysis. The results showed that dissolution channels expanded preferentially upward from the initial artificial channel location, driven by gravity-induced concentration gradients. Channel formation occurred only above a critical flow rate of 0.01 mL/min, whereas lower flow rates produced a slowly advancing dissolution front. Elkhoury et al. (2015) conducted reactive flow experiments in fractured dolomitic anhydrite cores, using an optical profilometer to visualize fracture geometry. They found that the ratio of advective to reactive timescales controls permeability evolution: when the ratio is much greater than one, dissolution localizes along flow paths, which leads to reaction-front instabilities and rapid permeability increase; when less than one, dissolution is more uniform across the fracture. The experimental approaches described above, implemented across micrometre to centimetre, enable the observation and quantification of changes in pore space or fracture channel geometry by tracking boundary movement at the fluid–solid interface using optical or CT imaging. In many studies, fractures are created in rock mechanical experiments, which poses challenges for reproducibility and experimental consistency. Moreover, the effect of the initial fracture surface geometry on dissolution behaviour is often overlooked. As shown in Figure 2.2 (a), the fracture space is tortuous. For example, the region at A1 features a shallow and wide flow path, while A2 represents a deep and narrow one, as illustrated in Figure 2.2 (b). These variations can locally influence fluid flow velocity and lead to dissolution heterogeneity. In this study, we chose to greatly simplify the geometry of our fracture channels (Figure 2.2 (c)) to improve control and reproducibility. We investigate how the initial fracture geometry affects reaction kinetics and advective transport within the fracture, and how these processes shape the subsequent evolution of the channel geometry.

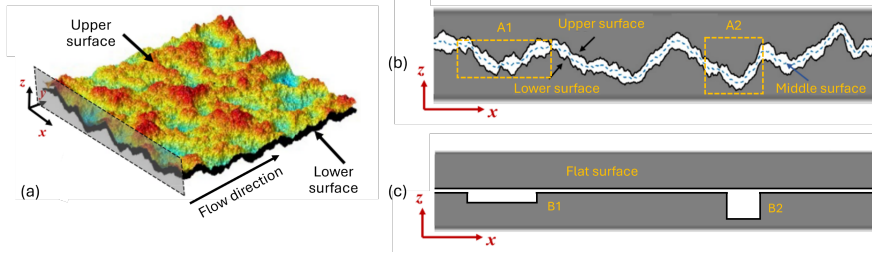


Figure 2.2. (a) Numerically generated 3D model of a fracture. (b) The corresponding 3D void space structure, with A1 and A2 indicating two representative flow paths: A1 corresponds to a shallow and wide region, while A2 represents a deep but narrow region. (c) A simplified, rectangular-shaped fracture space, where B1 and B2 correspond to A1 and A2 in (b). Models employing such composite aperture representations are commonly referred to as 2.5 D models (adjusted from Villamor-Lora et al., 2023).

In terms of the dissolution pattern transitions, most studies to date are limited to microchip fluid injection setups or millimetre scale core flow-through experiments. While the $Pe - Da$ framework is applicable, there is a lack of studies using decimetre scale samples to capture the transition between different dissolution regimes. In particular, few studies have investigated fractures of sufficient length to determine whether dissolution reaches a steady or equilibrium state over time. Meanwhile, numerical simulations can complement experimental observations by providing detailed profiles of solute concentration and fluid flow velocity, offering insights into complex dynamics that are difficult to measure directly in laboratory experiments. Menke et al. (2023) conduct pore-scale acid dissolution simulations using OpenFOAM and identify channeling as a distinct dissolution pattern, in addition to the commonly observed uniform, compact, and wormhole types. COMSOL Multiphysics is also widely used for modelling dissolution-transport processes, enabling the development of numerical models through its Chemical Reaction and Transport Modules (Ling et al., 2023).

Despite work at micro and centimetre scales, it remains unresolved at the decimetre scale how initial fracture geometry in rock salt, together with advective and diffusive transport (Péclet) and reaction kinetics (Damköhler), governs transitions among dissolution patterns, the evolution of fracture surface, and permeability growth. To bridge the gap, a flow-through experimental setup is developed using a flat glass plate over a rock salt plate with a rectangular channel, representing simplified fracture geometries. We employ three initial fracture geometries. The sample length is extended to 20 cm to assess whether an equilibrium state can be reached under continuous flow. Experiments with varying flow rates and salt concentrations are conducted to explore dissolution behaviours within the Péclet–Damköhler ($Pe - Da$) framework. We use a COMSOL-based 3D reactive transport model of the initial and final geometries to complement the experiments by simulating fluid velocity and solute concentration fields.

2.2 Methods and materials

Commercially sourced pink rock salt plates measuring 20 cm in length, 10 cm in width, and 2.5 cm in thickness are used in this study. X-ray Diffraction (XRD) and X-ray

Fluorescence (XRF) spectroscopy show that the samples consist of 99.76% sodium (Na) and chlorine (Cl) by weight, with trace impurities, including Fe, Mg, Br, and Al (Appendix A1). These impurities likely contribute to the pink coloration of the rock salt samples.

2.2.1 Fabrication of fracture channel

The fabrication of a fracture channel within a rock salt sample is a two-step process, illustrated in Figure 2.3. First, the rock salt block is cut into rectangular samples measuring 20 cm in length, 3.3 cm in width, and 2.5 cm in thickness. These samples are then encapsulated in dark epoxy within a custom-made mould. The epoxy is prepared by mixing resin (EP101UV) and hardener (EP123). To enhance visual contrast between the moderately transparent rock salt and the epoxy, a black polyester pigment paste (RAL 9005 Jet Black) is added. The mixture is stirred continuously for 20 minutes to achieve uniformity and homogeneity. Subsequently, degassing is performed using a vacuum pump to eliminate air trapped bubbles. Prior to pouring the degassed epoxy into the mould containing the rock salt sample, the mould's interior surface is lightly coated with Vaseline to facilitate easy retrieval after curing. The assembly is then left undisturbed for 7 days to allow the resin to fully cure and form a strong bond with the rock salt sample. After this curing period, the rock salt sample, now firmly encapsulated in black epoxy, is removed from the mould (Figure 2.3 (a)). In the second step we fabricate a cuboid channel on the sample surface connected with cubic grooves (1 cm × 1 cm × 1 cm) near the inlet and outlet (Cable 1 and Cable 2) (Figure 2.3 (b-c)) using a milling machine (Snapmaker 350, accuracy: ± 0.15 mm). The grooves at the in- and outlet act as buffer zones, ensuring stable fluid flow across the fracture and preventing pressure build-up (Figure 2.3 (c-d)). Following the milling of the fracture channels, silica glue is applied along the boundary, which is then allowed to cure for one week, ensuring a secure and durable seal between the rock salt sample and the glass plate (Figure 2.3 (d)). In our experiment, three different fracture channels geometries are utilized:

- 1) G-I, 3.3 x 15 x 200 mm (depth x width x length) (Figure 2.3(c1) and (d2)).
- 2) G-II, 10 x 5 x 200 mm (Figure 2.3(c2) and (d3)).
- 3) G-III, 4 x 4 x 200 mm.

G-I and G-II fractures serve as simplified initial fracture roughness profiles representing shallow, wide channels and deep, narrow channels, respectively. Both maintain an identical initial fracture channel volume of 10000 mm³ but differ in reactive surface areas, with G-I having a surface area of 7920 mm² and G-II of 10600 mm². Additionally, one sample with fracture geometry G-III is fabricated, featuring a reactive surface area of 8200 mm² and a fracture channel volume of 3200 mm³.

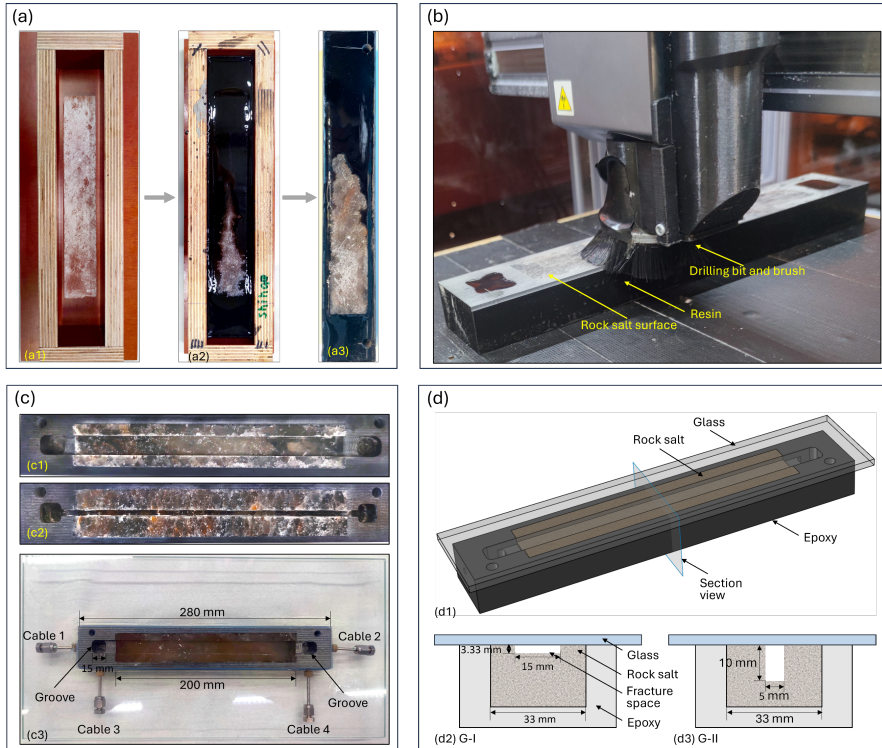


Figure 2.3. Sample preparation procedure: (a) Rock salt sample encapsulated in epoxy. (b) Fabrication of the channel on the sample surface using a milling machine (Snapmaker 350). (c) Top views illustrating fracture geometry I (G-I) in (c1), Geometry II (G-II) in (c2), and the sample bonded to a transparent glass plate in (c3). (d) Final assembled sample: (d1) 3D view; (d2) cross-section of G-I; (d3) cross-section of G-II.

2.2.2 Experimental setup and procedures

Detailed experimental conditions are provided in Table 2.1. Each experiment begins by injecting approximately 140 mL of saturated brine solution through the fracture channel at a flow rate of 0.1 mL/min. This initial step ensures the removal of residual air from the fracture channel and pressure transducers, while simultaneously checking for potential leakage. After confirming that no leakage is present, an undersaturated NaCl solution with different initial concentrations (C_{ini}) relative to the saturation concentration (C_{sat}), specifically, $C_{ini}/C_{sat} = 11\%$, 72% , 83% , is injected through the fracture channel at flow rates of either 3 mL/min or 9 mL/min to investigate the effect of fluid properties on fracture geometry evolution, using a Teledyne ISCO D-Series 1000D pump. To ensure consistency across experiments, an equal total volume of 463 mL of H_2O is passed through each experimental system.

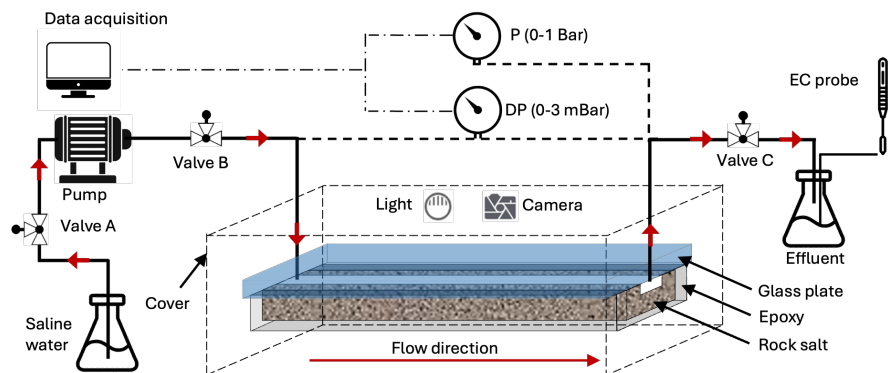


Figure 2.4. Diagram of fluid-injection experiment setup

After meso-model fabrication (i. e., decimetre scale), the setup is connected to a flow visualization system, as depicted in Figure 2.4. To shield camera recordings from external disturbances the sample is enclosed within a black cover equipped internally with blue parallel LED lighting. A camera (Canon 350D) equipped with a macro lens (Canon EF 24 mm 1:1.4 L Ultrasonic) is installed directly above the model, and captures images of the dissolution process every 30 seconds or 90 seconds. Each captured image has a resolution of 2304×3456 pixels, corresponding to a spatial resolution of $70 \mu\text{m}$ per pixel. Additionally, effluent samples of the fluid exiting the system are collected at intervals of either 3 or 5 minutes, and the dissolved mass of rock salt is determined post-experimentally using electrical conductivity measurements (MultiLine® Multi 3630 IDS). The relationship between salt concentration and electrical conductivity is provided in Appendix A2. The total dissolved salt mass is calculated as follows: because the injected fluid concentration is constant, the dissolved rock salt mass is obtained by subtracting the injected salt mass from the effluent salt mass. The fluid regime in all experiments falls within the laminar flow range (see Appendix A3).

Changes in fluid pressure along the fracture are continuously monitored with a differential pressure transducer (Endress+Hauser, 10 mbar, accuracy at ± 0.01 mbar) and an absolute pressure transducer (Endress+Hauser, 1000 mbar, accuracy at ± 0.01 mbar). Subsequently, the evolution of fracture permeability is calculated using Darcy's law. A stable pressure drop is observed throughout the experiments. The permeability of all channels (G-I, G-II, and G-III) is approximately 7500 Darcy and exhibits no measurable change during the experiments (Appendix A4).

Table 2.1 Summary of flow-through dissolution experiments

Exp	C_{in} (g/L)/ (mol/L)	Q (mL/min)	V (m/s)	Channel size (mm)	Reaction surface area (mm ²)	Total injection time (min)	Total injection brine (mL)
S1	40/ 0.684	3	1×10^{-3}	3.3 -15 - 200 (G-I)	7920	165	496
S2	40/ 0.684	9	3×10^{-3}	3.3 -15 - 200 (G-I)	7920	55	496
S3	260/ 2.738	3	1×10^{-3}	3.3 -15 - 200 (G-I)	7920	258	773
S4	260/ 2.738	9	3×10^{-3}	3.3 -15 - 200 (G-I)	7920	86	773
S5	40/ 0.684	3	1×10^{-3}	10 - 5 - 200 (G-II)	10600	165	496
S6	40/ 0.684	9	3×10^{-3}	10 - 5 - 200 (G-II)	10600	55	496
S7	260/ 2.738	3	1×10^{-3}	10 - 5 - 200 (G-II)	10600	258	773
S8	260/ 2.738	9	3×10^{-3}	10 - 5 - 200 (G-II)	10600	86	773
S9	300/ 5.133	2	0.6×10^{-3}	3.3 -15 - 200 (G-I)	7920	428	856
S10	40/0.684	9	9.3×10^{-3}	4 - 4 - 200 (G-III)	8200	55	496
S11	260/ 2.738	3	1×10^{-3}	3.3 -15 - 200 (G-I)	7920	258	773

Note: C_{sat} represents the saturated concentration of the NaCl solution, which is 6.16 mol/L in this study. Accordingly, concentrations of 11%, 72%, and 83% of saturation correspond to 0.68 mol/L (40 g/L), 4.4 mol/L (260 g/L), and 5.13 mol/L (300 g/L), respectively. Channel sizes are reported in depth–width–length. S9 employs a higher salt concentration (300 g/L) and lower flow rate (2 mL/min). S10 uses the same fluid conditions as S1 and S5 but with a different fracture geometry. S11 replicates S3.

2.2.3 Image processing method

2.2.3.1 From photo to 2D fracture geometry

We calculate the dissolution area, defined as the area of rock salt removed as seen from the top view. Initially, the original images are cropped to focus on the rock salt sample, and each file is systematically labelled according to the timestamp of capture. Following this, all images are converted to grayscale using the “rgb2gray” function (Figure 2.5 (a)–(b)). The first image is designated as the reference (T0), and subsequent images are compared to this baseline, with the temporal difference denoted as (T–T0). The image difference is computed using the “abs” function to ensure that all pixel intensity values remain positive. To enhance visibility, the absolute difference image is amplified 15 times (Figure 2.5 (b)–(c)). This produces images where light areas represent dissolved sections and dark areas indicate undissolved regions (Figure 2.5 (c)). A threshold is then applied to create a binary image, separating dissolved and undissolved regions. The threshold value is kept consistent across the image set to ensure comparability between time steps. To reduce noise and improve the continuity of dissolved regions, hole filling and morphological closing (using a predefined structuring element) are applied to remove small artefacts and close gaps within the white regions (Figure 2.5 (d)). The dissolution area is quantified by summing the number of white pixels, with each white pixel representing a unit area of dissolution. When needed, the pixel count is converted to a physical area using the image scale. Based on this, the relationship between the dissolution area and the cumulative injected water volume is calculated. The slope of dissolution area versus water volume is defined as “ α ” (unit: cm²/mL).

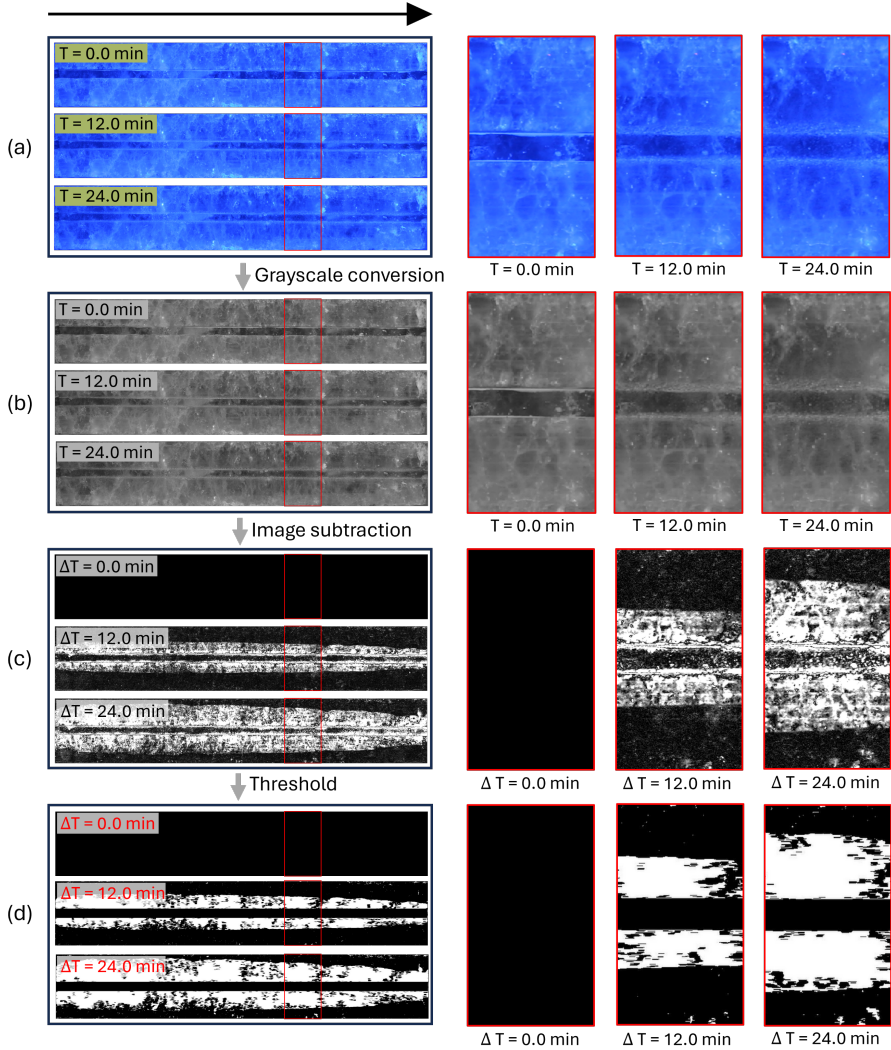


Figure 2.5. The raw image from S5 recorded by the camera is displayed in two sections. On the left side, each image displays a whole view of the sample. The pictures on the right show close-up sections of the images on the left, highlighted within red frames, to focus on specific areas. (a) Raw image. (b) Grayscale-converted image. (c) Subtracted image, where dark areas indicate undissolved rock salt and white areas indicate dissolved regions. (d) Image after thresholding and morphological processing. The black arrow at the top shows the flow direction.

2.2.3.2 Microcomputed Tomography

Given the consistent initial channel geometry produced by the milling process, we scan only the post dissolution geometry using a TESCAN CoreTOM at a voxel resolution of 100

micrometres. Reconstruction is performed in PantheraTM, and the 3D models are then processed in Avizo ©2023, including cropping and thresholding to improve the visibility of the rock salt sample and fracture channel (Figure 2.6 (a–b)). The segmented surface is exported and further processed in MeshLab for mesh cleaning and segmentation. MeshLab is used to cut the reconstructed surface and isolate the dissolution region while removing irrelevant parts of the model (Figure 2.6 (c)).

MATLAB is then used to map the reaction surfaces in both 3D and contour formats based on STL files generated by MeshLab (Figure 2.6 (d–e)). Dissolution mass, both local and total, is quantified by calculating the volume difference between the initial and final fracture channels. To assess spatial variations along the flow direction, each sample is divided into five equal sections (Sections 1–5) and the volume loss is calculated for each section (Figure 2.6 (e)). The dissolution rate (R , unit: g/mL) is defined as the dissolved mass per unit injected water volume. Finally, an interpolation method is applied to smooth the reaction surface, and SolidWorks is used to reconstruct and assemble the complete fracture flow space before importing the geometry into COMSOL for chemical fluid reaction simulations. The image processing workflow for the 3D reaction surface is provided in Appendix A5.

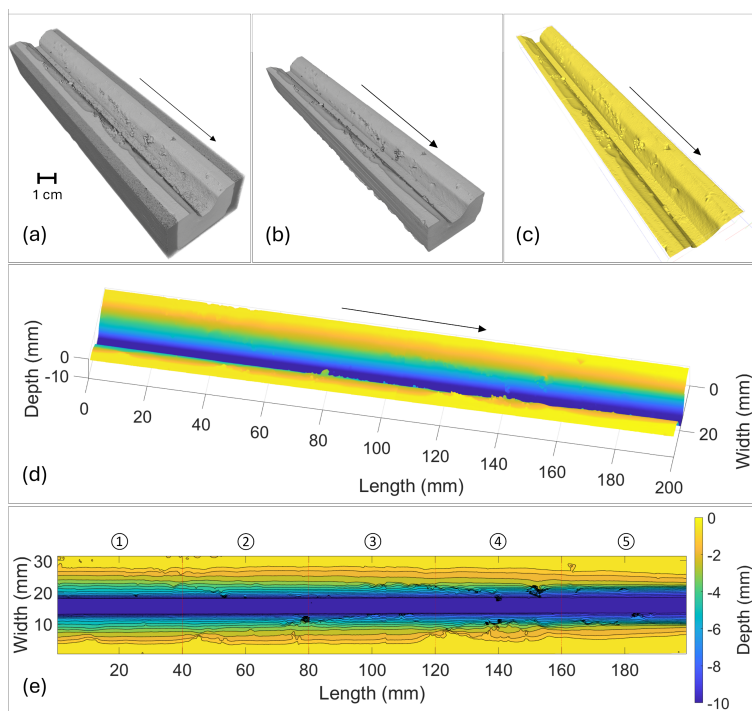


Figure 2.6. Image processing workflow based on CT data of S7. (a) A 3D reconstruction of the rock salt sample, including the surrounding mould. (b) The isolated geometry of the rock salt sample. (c) The exposed reaction surface after cropping in MeshLab. (d) A 3D surface representation of the reaction surface generated in MATLAB. (e) Corresponding contour maps along the depth direction. The surface is divided into five equal sections along the fluid flow direction, and 20 contour lines are generated using MATLAB to visualize surface. The CT data processing method has a precision of 0.1 mm.

2.2.4 Coupled reactive and transport model

A model is set up to simulate reactive flow through a rock salt fracture exposed to an undersaturated saline solution, aiming to analyse fluid velocity and concentration distributions. The pre- and post-experimental surface geometries serve as inputs to a coupled reactive transport model in COMSOL Multiphysics 6.1. The Reaction Flow module solves the Navier–Stokes equations to determine velocity and pressure fields, while the Transport of Diluted Species module models the mass transfer process. The simulation operates under the following assumptions: (1) The simulation is solved as a stationary problem; (2) The dissolution rate of rock salt is assumed to be linearly related only to the concentration gradient of the brine at the boundary; (3) Only pure rock salt is considered and the content of insoluble substances is zero; (4) The injection solution is incompressible.

2.2.4.1 Constitutive laws

To simulate rock salt dissolution and fluid transport, the transport problem is described by the laminar flow equations (Eqs. (2.1) – (2.3)). Eq. (2.1) expresses the fluid momentum balance using the Navier–Stokes formulation, Eq. (2.2) enforces mass conservation for an incompressible fluid, and Eq. (2.3) defines the constitutive relation for viscous stress.

$$\rho(v \cdot \nabla)v = \nabla \cdot [-pI + K] \quad (2.1)$$

$$\rho \nabla \cdot v = 0 \quad (2.2)$$

$$K = \mu(\nabla v + (\nabla v)^T) \quad (2.3)$$

where $\rho [kg/m^3]$ represents the fluid density; $v [m/s]$ is the velocity field of the fluid; $p [Pa]$ is the pressure within the fluid; I is identity tensor; $K [Pa]$ represents the viscous stress tensor.

The reaction process is modelled by Eqs. (2.4) – (2.6). Eq. (2.4), the transport equation with a source/sink term, expresses the conservation of solute mass, accounting for both diffusion ($\nabla \cdot J$) and convection ($v \cdot \nabla c$), as well as reactions occurring within the fluid (R). Eq. (2.5) describes the relationship between the diffusive flux (J) and the concentration gradient (∇c), indicating that the flux is proportional to the gradient and directed from regions of high concentration to low concentration (negative value). Eq. (2.6) defines the dissolution rate in terms of the concentration difference at the rock salt–fluid interface.

$$\nabla \cdot J + v \cdot \nabla c = R \quad (2.4)$$

$$J = -D \nabla c \quad (2.5)$$

$$R(c) = k(c_{sat} - c) \quad (2.6)$$

where ($\nabla \cdot J$) is divergence of the flux J ($mol/m^3 \cdot s$); ($v \cdot \nabla c$) is the convective term ($mol/m^3 \cdot s$); R is the rate of production or consumption due to chemical reactions ($mol/m^3 \cdot s$); J is the diffusive flux ($mol/m^2 \cdot s$); D is the diffusion coefficient (m^2/s), the value is $10^{-9} m^2/s$. ∇c is the gradient of concentration (mol/m^4); $R(c)$ is the surface reaction rate ($mol/m^2 \cdot s$); k is the mass transfer coefficient (m/s). The value is $10^{-4} m/s$ (Ling et al., 2023).

2.2.4.2 Geometry and boundary conditions

We use the initial S1 geometry, i.e. prior to dissolution, as an example to introduce the geometry and boundary conditions (Figure 2.7 (a)). The fracture channel is composed of six faces: the top face represents the interface between the flowing fluid and the transparent glass, which is defined as a non-reaction boundary. Surface 1 and Surface 2 serve as the inlet and outlet of the model, respectively. At Surface 1, constant flow velocity and salt concentration are applied, while Surface 2 is set to a zero-pressure boundary condition. The remaining three faces, including the sides and bottom face, are defined as reactive surfaces. For the numerical models before dissolution, the only variation is in the size of the model, maintaining a rectangular shape but with different heights and widths.

For the numerical models after dissolution, the boundary conditions remaining the same, whilst the model geometry is reconstructed based on 3D data from the reaction surface (Section 2.2.3.2) (see Figure 2.7 (b)). All parameters used in numerical modeling are listed in Table 2.2. A normal or fine mesh strategy is applied for discretization, resulting in approximately 48,000 elements.

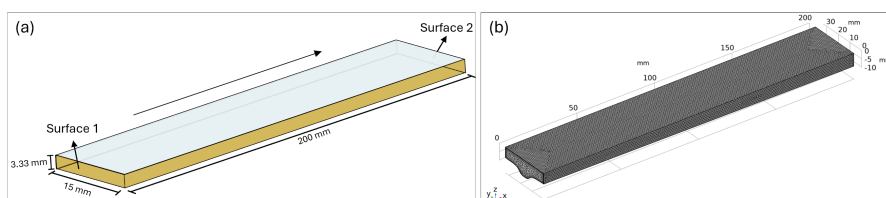


Figure 2.7. (a) The geometry and boundary diagram of the numerical model for S1 before dissolution; (b) The meshed geometry of the numerical model for S5 after dissolution.

Table 2.2 Model calculation parameters

Parameter	Variable	Value	Unit
Dynamic viscosity	μ	1e-3	Pa · s
Diffusion coefficient	D	1e-9	m ² /s
Mass transfer coefficient	k	1e-4	m/s
Fluid flow rate	Q	2; 3; 9	m/s ³
Initial concentration	C_{ini}	684/ 4449	mol/m ³
Saturated concentration	C_{sat}	6160	mol/m ³

Note: C_{ini} values are 684 mol/m³ (40 g/L) and 4449 mol/m³ (260 g/L), while C_{sat} is 6160 mol/m³ (360 g/L).

2.3 Results

2.3.1 Fracture geometry evolution

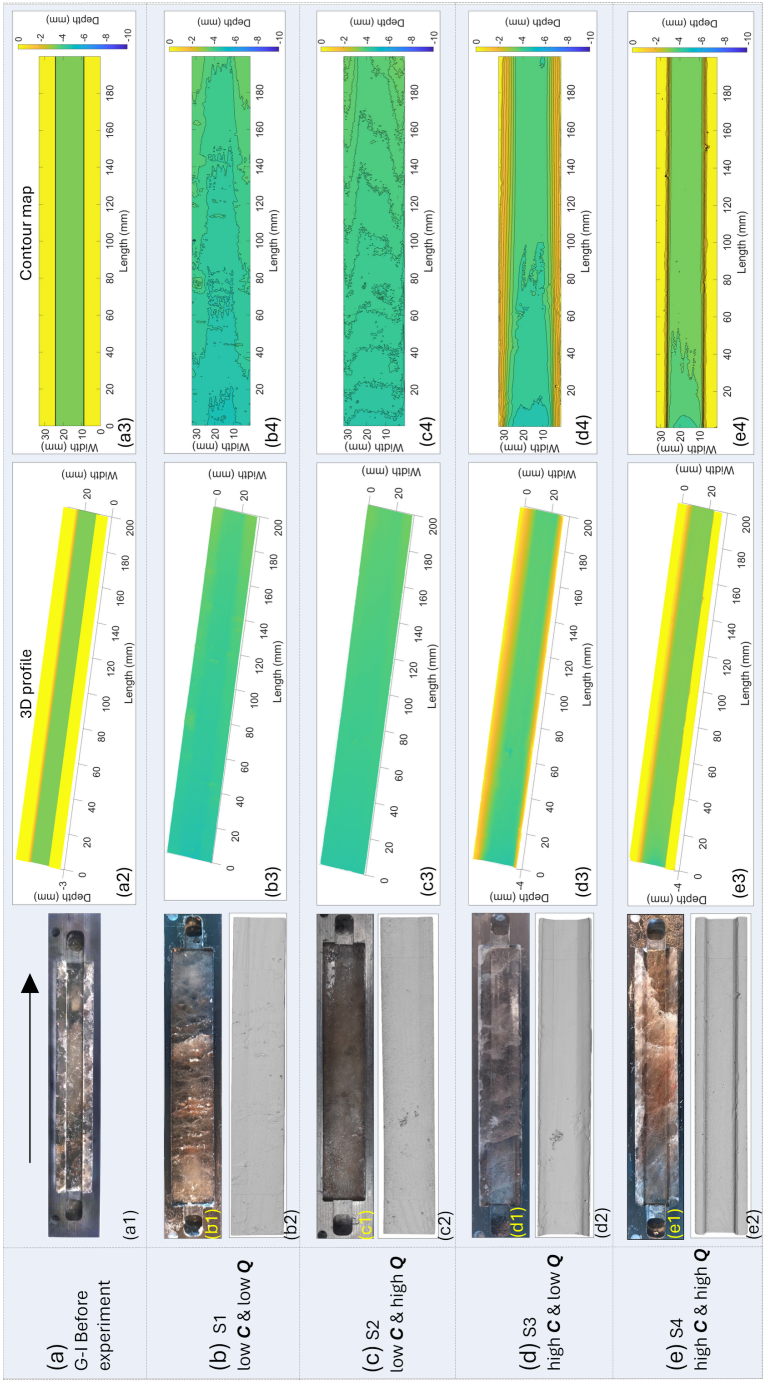
2.3.1.1 Dissolution pattern

A comparison of pre- and post-dissolution camera images for all samples shows that dissolution occurs along the fracture length, leaving distinct streamlines on the surface (S1 - S8 in Figure 2.8; S9 - S11 in Appendix A6). The 3D surface plots and contour maps show that, independent of initial geometry, inflow concentration or flow rate, dissolution consistently occurs heterogeneously along the sample. More dissolution of rock salt occurs near the inlet, and less dissolution near the outlet across all samples. Additionally, more dissolution is observed in the upper parts of the channel than in the lower parts along the depth direction. Contour maps illustrate these patterns: all convex contours (i.e., bulging along the flow direction and smoothly curved) align with the flow direction and exhibit symmetry along the central line. Section views further illustrate this by comparing post-dissolution cross-sectional profiles at various distances from the inlet with the initial profiles for samples S1 and S5. (Figure 2.9). The post-dissolution profiles are lower than the initial ones in the depth direction, indicating salt dissolution along the channel depth. With increasing distance from the inlet, the profile depth also increases while retaining a consistent upward-converging arc shape, indicating enhanced dissolution along the fracture corners.

The shallow and wide channel, fracture geometry (G-I), is used for samples S1 through S4 (Figure 2.8 (a)). For S1 and S2, conducted at low concentrations, rock salt along both sides of the fracture channel is completely dissolved, regardless of flow rate (Figure 2.8 (b)-(c)). In contrast, for S3 and S4 at high concentrations, some salt remains partially undissolved along both sides, with less dissolution at high flow rates than at low flow rates (S3 vs. S4; see Figure 2.8 (d)-(e)).

The deep and narrow channel, fracture geometry G-II, is used for samples S5 through S8 (Figure 2.8 (f)). Complete side-boundary dissolution occurs only in S5, conducted under low concentration and low flow rate (Figure 2.8 (g)), while some boundary material remains in S6, S7, and S8 (Figure 2.8 (h)-(j)). At low concentrations, greater dissolution at lower flow rates (S5) results in a relatively flat post-dissolution geometry, whereas S6 (high flow rate) shows limited dissolution, mainly along the edges. In S7 and S8 (high concentrations), the post-dissolution geometry changes minimally, with substantial rock salt remaining along both sides of the flow path. Dissolution is less at higher flow rates (S8) than at lower ones (S7) (Figure 2.8 (i)-(j)).

When comparing samples with G-I (shallow, wide channel) and G-II (deep, narrow channel) fracture geometries, G-II samples (S5–S8) generally retain their original shape. In contrast, under low salt concentrations, G-I samples (S1 and S2) develop a planar geometry after dissolution.



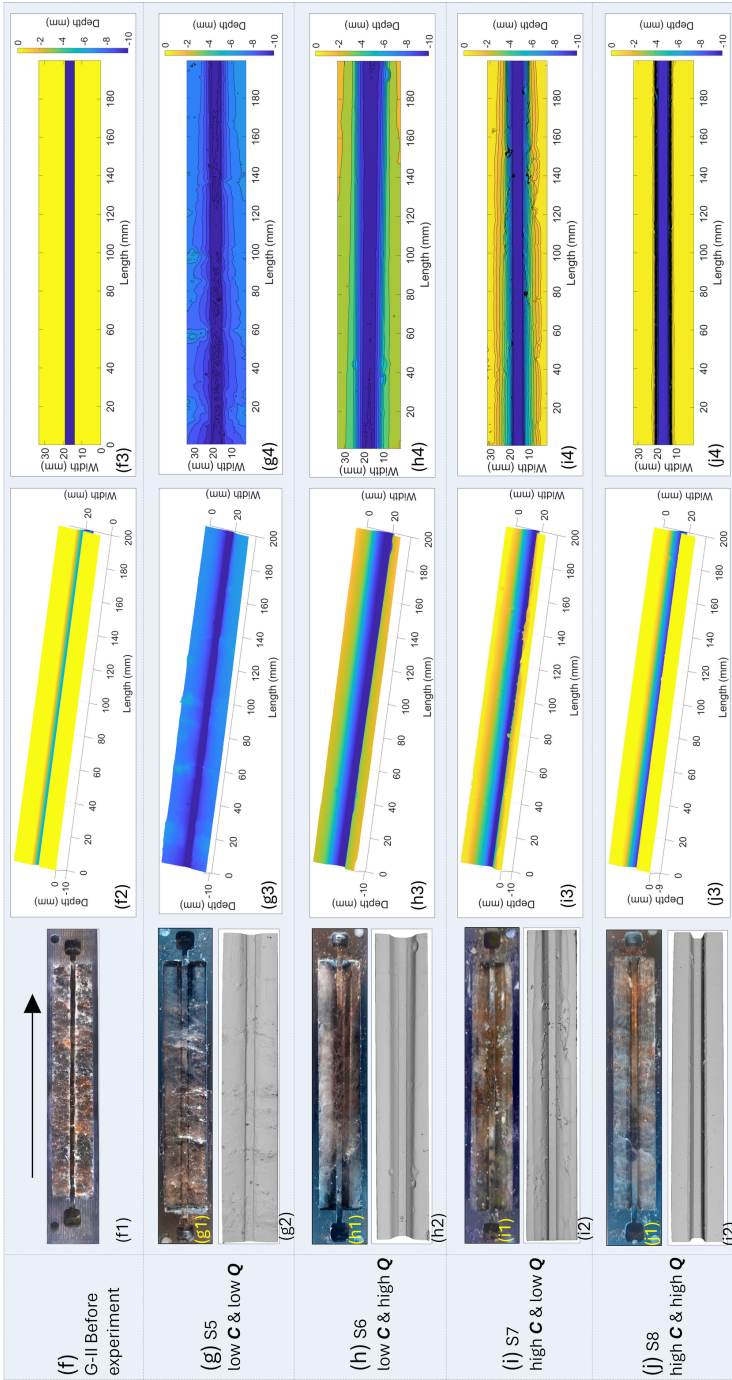


Figure 2.8. (a) shows the reaction surfaces of G-II before dissolution. (b)–(e) present the post-dissolution surfaces of S1–S4, each including a camera image, micro-CT scan, 3D surface plot, and contour map. (f) shows the reaction surfaces of G-II before dissolution, while (g)–(j) display those of S5–S8 after dissolution. In the 3D surface and contour maps, yellow indicates higher elevations and blue indicates lower regions, with a scale ranging from 0 to -10 mm.

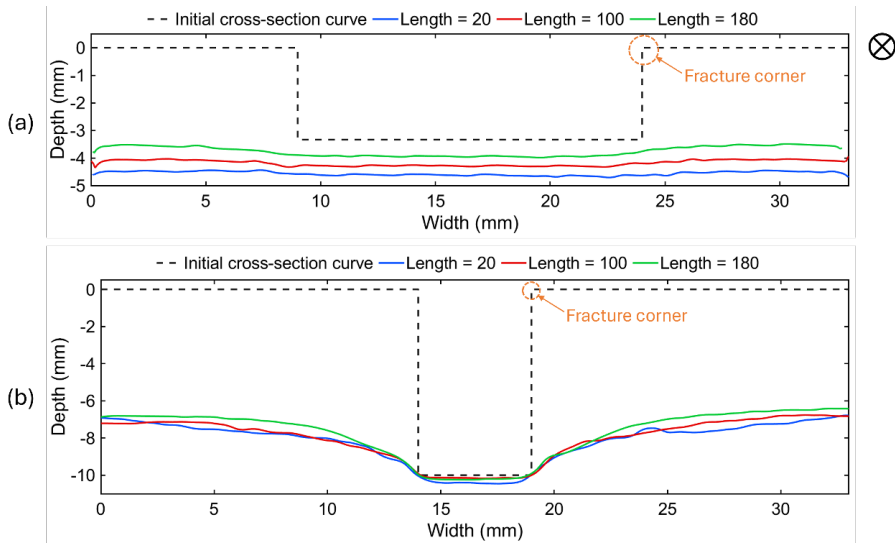


Figure 2.9. (a) and (b) show cross-sectional profiles before and after dissolution in samples S1 and S5, respectively, based on micro-CT images. The dashed line represents the initial profile before dissolution. Blue, red, and green curves show post-dissolution profiles at 20 mm, 100 mm, and 180 mm along the flow path, respectively. The orange circle marks the fracture corner before dissolution, while the black circle with an "x" indicates flow direction perpendicular to the page, into the plane.

2.3.1.2 Dissolution area evolution

At the start of injection, the channel boundaries appear parallel, as observed in the 2D fracture geometry of sample S5 (Figure 2.10 (a)). As injection continues, enhanced dissolution occurs in the fracture corners of the sample. The fluid front advances symmetrically toward the epoxy–rock salt interface in the width direction. Dissolution is non-uniform along the length, with the decreasing distance between boundary lines along the flow direction indicating a reduction in dissolution mass downstream (Figure 2.10 (b)–(d)). Similar heterogeneous dissolution along the flow path is observed in other samples. Eventually, the boundary reaches the epoxy–rock interface, indicating complete dissolution of the side regions (Figure 2.10 (e)). The evolution of dissolution area with injected water volume is shown in Figure 2.9 (f). Initially, the area increases almost linearly (point “a” to “d”). As side dissolution begins (point “d”), the slope decreases, and once dissolution reaches the epoxy boundary, the slope stabilizes (after point “e”).

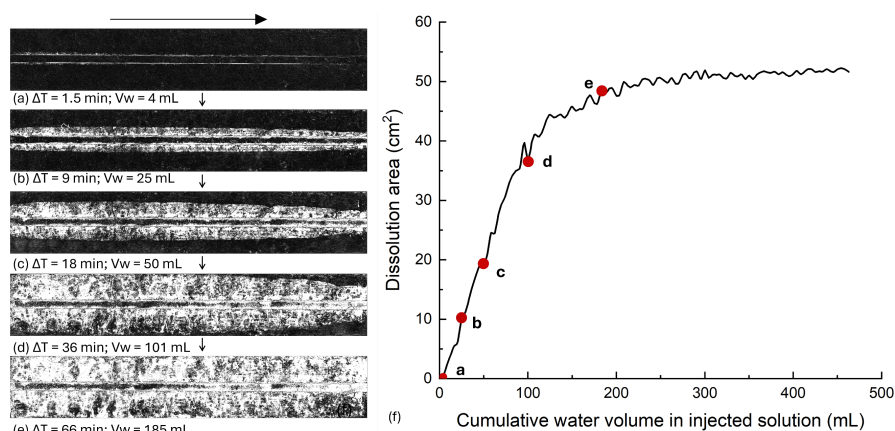


Figure 2.10 illustrates the evolution of the solid-fluid interface over injection time of S5. Bright pixels represent dissolved regions occupied by flowing fluid, while dark pixels correspond to undissolved rock salt. (f) shows the dissolution area (white region) versus cumulative injected water volume, with red dots (a-e) corresponding to the moments shown in (a)-(e).

2.3.2 Dissolution mass and rates

For S1 and S2 with G-I geometry (shallow and wide) conducted at low concentrations, the initial slope of the dissolution area versus cumulative water volume is higher for S1 ($\alpha = 0.27 \text{ cm}^2/\text{mL}$), which was conducted at a lower flow rate. This value is twice that of S2 ($\alpha = 0.13 \text{ cm}^2/\text{mL}$), which was conducted at a higher flow rate (Figure 2.11). After reaching the epoxy boundary, the slopes decrease to $0.02 \text{ cm}^2/\text{mL}$ and $0.03 \text{ cm}^2/\text{mL}$, respectively. For S3 and S4, the dissolution area increases almost linearly. Both conducted at high concentrations, the slope remains higher for the low flow rate sample (S3, $\alpha = 0.06 \text{ cm}^2/\text{mL}$) compared to the high flow rate sample (S4, $\alpha = 0.04 \text{ cm}^2/\text{mL}$). Overall, the slope of dissolution area versus injected water volume follows the order: $S1 > S2 > S3 > S4$. A similar trend is observed in samples S5–S8 (fracture geometry G-II, narrow and deep). The slope of dissolution area versus injected water volume follows the order: $S5 > S6 > S7 > S8$. Compared to samples with fracture geometry G-I, those with G-II exhibit very similar slopes for the same salt concentration and flow rate.

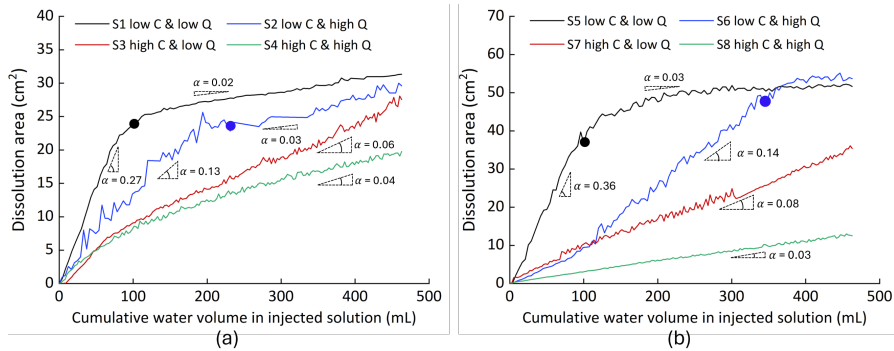


Figure 2.11. (a) and (b) show the evolution of the 2D dissolution area vs. cumulative injected water volume for samples S1–S4 (G-I) and S5–S8 (G-II), respectively. The marks on the S1, S2, S5 and S6 curves, indicate the point at which the solid-fluid interface begins to reach the epoxy boundary. The unit of k in the plot is cm²/mL.

The total dissolved mass of samples with geometry G-I (shallow, wide) decreases in the order: S1 (35 g) > S2 (32 g) > S3 (23 g) > S4 (18 g) (Figure 2.12 (a)). A similar trend is observed for samples with geometry G-II (deep, narrow), with the dissolved mass decreasing in the order: S5 (108 g) > S6 (60 g) > S7 (31 g) > S8 (16 g) (Figure 2.12 (b)). Under identical fluid conditions, samples with fracture geometry G-II exhibit higher dissolution mass than those with G-I, ranging from approximately one to three times greater.

In terms of dissolution rate, all samples exhibit an initial sharp decline at the first measurement point, due to the use of a saturated solution to remove air from the fracture (Figure 2.12 (c) and (d)). Subsequently, the dissolution rate stabilizes as the fracture becomes filled with the injected undersaturated brine, which happens within the first two measurement points except for those samples with low concentration and low flow rates (S1 and S5). Low concentration leads to higher dissolution rates, and at low flow rate dissolution rates are higher than at high flow rate (compare Figure 2.12 (c) to Figure 2.12 (d)).

Local dissolution mass obtained from micro-CT images shows a decrease from the inlet (section 1) to the outlet (section 5) in all samples (Figure 2.13). For sample S5 with G-II fracture, the dissolution mass in sections 1 through 5 is 21.27 g, 21.07 g, 20.32 g, 19.74 g, and 18.91 g, respectively, indicating heterogeneous dissolution along the flow direction. Under same fluid conditions, S1 with a G-I fracture shows a lower dissolution mass in section 1 (8.49 g) compared to section 1 in S5 (21.27 g).

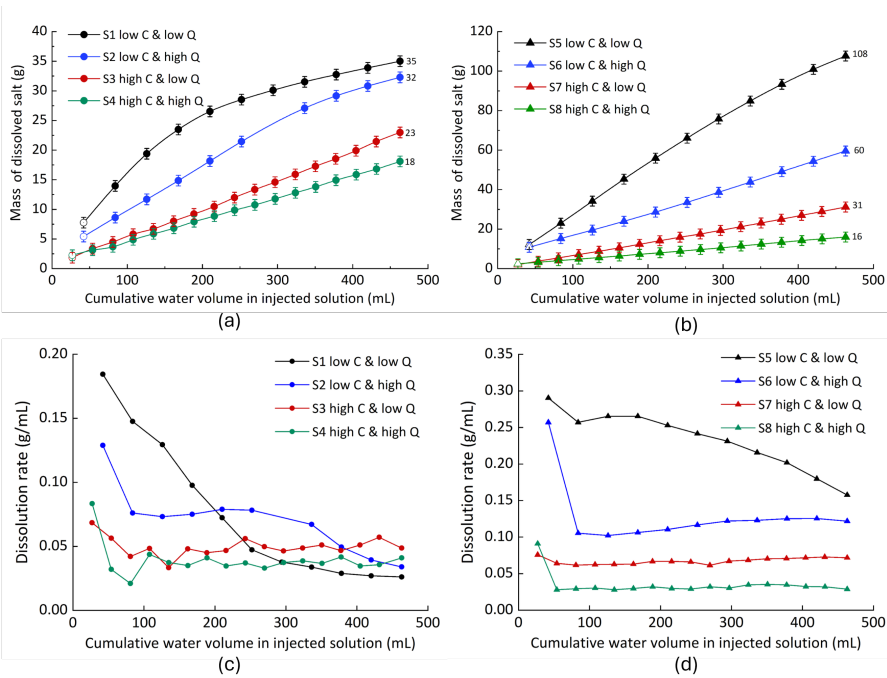


Figure 2.12. (a)–(b) show the salt dissolution mass vs. cumulative injected water volume for S1–S4 and S5–S8, respectively; (c)–(d) present the corresponding dissolution rates.

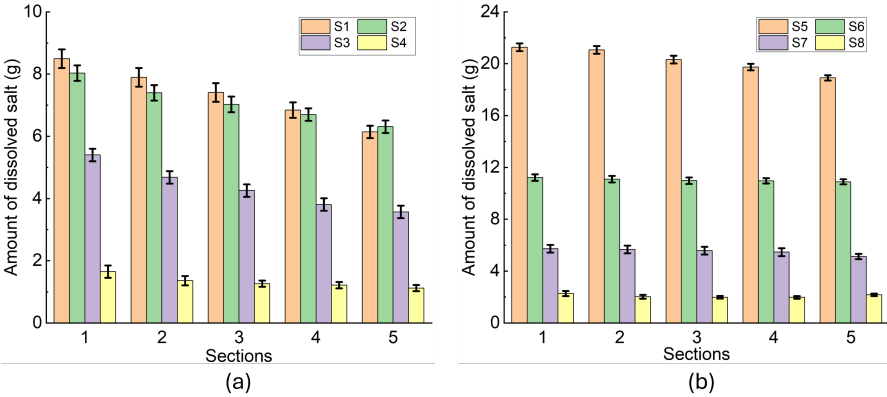


Figure 2.13. (a) and (b) display the total dissolution mass across different sections for S1–S4 and S5–S8, respectively.

2.3.3 Coupled reactive and transport model

Sixteen numerical models are created in COMSOL to represent the pre- and post-dissolution geometries of samples S1–S8. The concentration profiles of the post-dissolution states for S1–S8 are provided in Appendix A7. The analysis focuses on the velocity profiles and concentration distributions on Plane 1 (parallel to the XY plane) and Plane 2 (parallel to the YZ plane at $X = 100$ mm). Data along Line 1 and Line 2 (i. e., yellow dashed line) are extracted from different experiments (Figure 2.14).

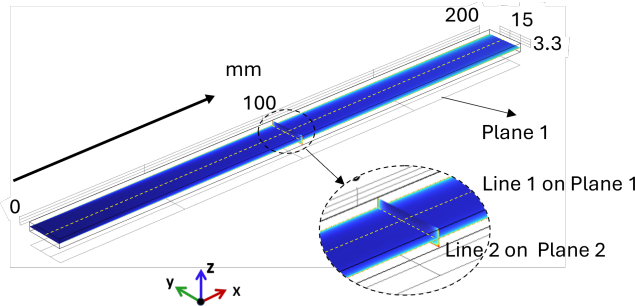


Figure 2.14. Data extraction locations.

2.3.3.1 Velocity profile

The fluid velocity on planes parallel to the XY plane ($Z = -1$ mm, -2 mm, -3 mm) is initially symmetric along the central axis parallel to the X-direction (Figure 2.15 (a–c)). Near the rock salt boundaries, the velocity approaches zero (blue regions), while it increases toward the central region (red regions). Before dissolution, velocity varies with depth. At $Z = -2$ mm, closer to the central part of the flow domain, the maximum velocity ($V_{\max} = 16 \times 10^{-4}$ m/s) is higher than at $Z = -1$ mm ($V_{\max} = 14 \times 10^{-4}$ m/s) and $Z = -3$ mm ($V_{\max} = 6.8 \times 10^{-4}$ m/s). Additionally, Plane 1 views (parallel to the YZ plane) show that fluid velocity is nearly zero at the channel boundaries and highest in the central region (Figure 2.15(d)).

After dissolution, the flow channel expands in both width and depth, leading to decreased velocity on the same planes compared to the pre-dissolution state (Figure 2.15 (a–d) vs. Figure 2.15 (e–h)). Enhanced dissolution occurs near the inlet, the flow space in this region increases, resulting in lower velocities relative to the outlet channel. The convex velocity contours are oriented opposite to the flow direction.

The velocity profile along Line 2 exhibits a convex shape of varying magnitude, determined by the initial fracture geometry and fluid flow rate (Figure 2.16 (a)). The velocity profile remains relatively uniform along the fracture length before dissolution, with a velocity of 16×10^{-4} m/s. After dissolution, the velocity near the inlet decreases to 6×10^{-4} m/s, while it reaches $V = 8 \times 10^{-4}$ m/s near the outlet, both lower than the pre-dissolution velocity profile (Figure 2.16 (b)).

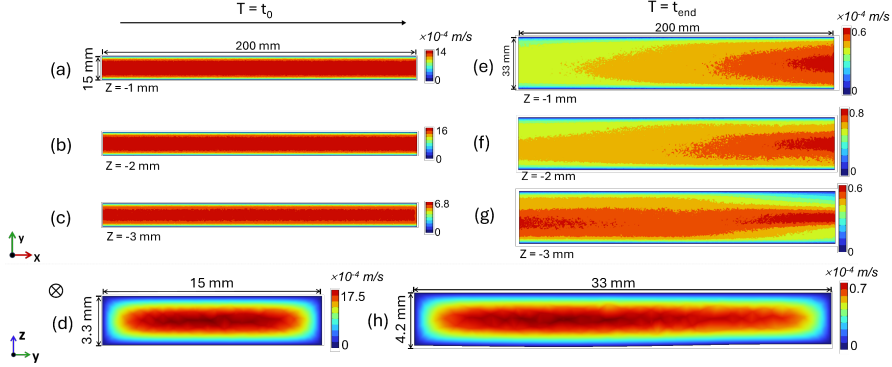


Figure 2.15. Example of S1. The X, Y, and Z axes represent the length, width, and depth of the numerical model, respectively. Velocity profiles at different planes parallel to the XY plane at the initial (a–c) and final (d–f) stages for $Z = -1$, $Z = -2$, and $Z = -3$, before and after dissolution. (g) and (h) show the velocity profiles in Plane 2 at the initial and final stages, respectively.

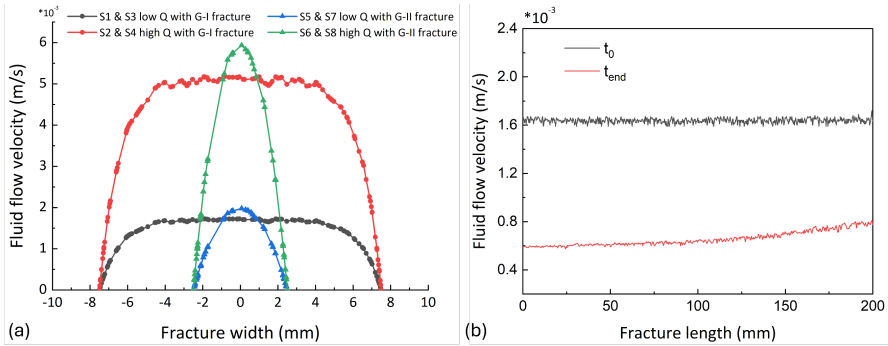


Figure 2.16. The fluid flow velocity along Line 2 for S1–S8 before dissolution. The fluid flow velocity along Line 1 for S1 before and after dissolution.

2.3.3.2 Concentration profile

Before dissolution, the concentration profile exhibits a streamline pattern with convex contours along the flow direction (Figure 2.17 (a–c)). Near the boundaries, the concentration approaches saturation, while it decreases toward the central region (blue areas). With increasing depth, the fluid transitions from an undersaturated to a saturated state due to its proximity to the rock salt. Along the flow path, concentration gradually increases from the inlet to the outlet. After dissolution, the streamline pattern remains, but the region of lower concentration expands due to the enlarged flow space caused by dissolution (Figure 2.17 (e–g)). The Plane 2 view (Figure 2.17 (d) and (h)) show that concentration remains near saturation at the boundaries, while the central region stays undersaturated.

Additionally, the concentration increases linearly along the fracture length in the flow direction (Figure 2.18). Under identical flow conditions, samples with G-II geometries consistently exhibit steeper concentration gradients than those with G-I geometries, suggesting that the undersaturated fluid entering from the inlet reaches higher saturation levels more effectively in G-II configurations (i. e., more dissolution in G-II samples). For instance, the gradient for sample S5 (0.32) is greater than that of sample S1 (0.24).

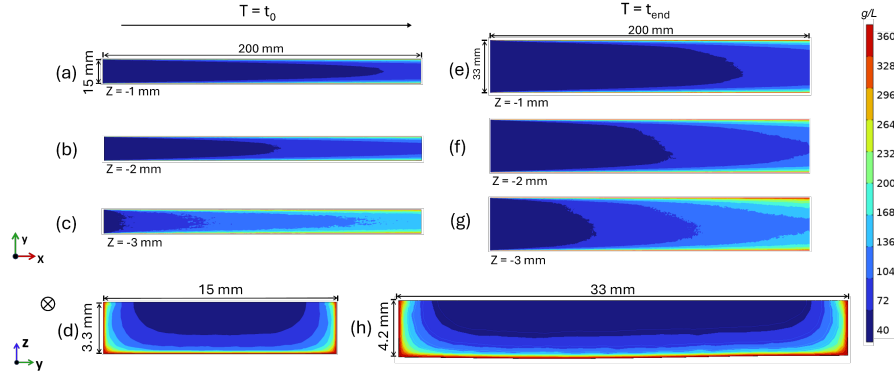


Figure 2.17. The concentration of NaCl profile at different planes parallel to the XY plane at the initial (a–c) and final (d–f) stages for $Z = -1$, $Z = -2$, and $Z = -3$, before and after dissolution. (g) and (h) show the concentration profiles in Plane 1 at the initial and final stages, respectively.

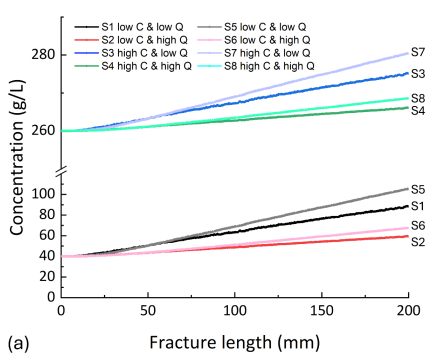


Figure 2.18. The concentration profile along Line 1 for S1–S8 before dissolution, with saturated brine defined as 360 g/L.

2.4 Discussion

2.4.1 Effect of initial geometry

The effects of two simplified fracture geometries (G-I and G-II) on fracture geometry evolution and dissolution mass are investigated. Analysis of the post-dissolution profiles (Figure 2.8) and dissolution area evolution (Figure 2.10) indicates that dissolution is heterogeneous, irrespective of fracture geometry. Rapid dissolution occurs near the inlet and along fracture corners. This phenomenon is attributed to the combined effects of reaction, diffusion, advection, and gravity-driven solute redistribution (Figure 2.19).

In concave regions, fluid velocity tends to be relatively low, promoting a diffusion-dominated regime in which the solute concentration at the rock–fluid interface rapidly approaches near-equilibrium conditions (Figure 2.19). As local concentration gradient decreases, the thermodynamic driving force for dissolution weakens, resulting in lower dissolution rates. This relationship is described by Fick's first law ($J = -D \partial C / \partial n$), which states that the diffusive flux is proportional to the local concentration gradient. This observation is further supported by velocity profile simulations, which show that the lower portion of the fracture exhibits a lower peak velocity (Figure 2.15 (c); $V_{\max} = 6.8 \times 10^{-4}$ m/s) and reaches saturation over a shorter distance (Figure 2.17 (c); saturation distance = 10 mm).

In convex regions, fluid advection is stronger and quickly sweeps away dissolved species, sustaining a large concentration gradient and enabling the system to remain far from equilibrium. This is supported by the simulated velocity profile, which shows the highest velocity (Figure 2.15 (a); 16×10^{-4} m/s) and the concentration profile, where the saturation distance extends up to 180 mm (Figure 2.17 (a)). This advection-dominated environment facilitates faster dissolution, aligning with the “roughness smoothing” effect noted in Zhou et al., (2022), whereby protruding topographies are preferentially dissolved over time. Similarly, the dissolution process induces a de-roughing effect on the fracture surface in our experiments. This is supported by the linear slope of the dissolution area versus cumulative injected water volume before the side rock salt begins to dissolve, followed by a decreasing slope as the fracture surface becomes smoother (Figure 2.10 (f)). At the millimetre scale, dissolution patterns transition from a wedge-shaped form to a more uniform profile as the flow rate increases (Zhou et al., 2022). Similarly, the transition in dissolution pattern, characterized by the dissolution of channel edges, is observed at higher flow rates in our experiments (S3, S4, S7 and S8 in Figure 2.8). Overall, regions dominated by advection, such as fracture tips, dissolve more rapidly, whereas concave regions, where diffusion dominates, dissolve more slowly. As a result, the fracture surface becomes progressively smoother along the flow direction. Moreover, gravity-driven solute redistribution within the fracture can further modulate local concentration profiles: higher solute concentrations often accumulate near the bottom of the fluid column, thereby sharpening the concentration gradient at higher elevations and promoting increased dissolution in those regions (Weisbrod et al., 2012).

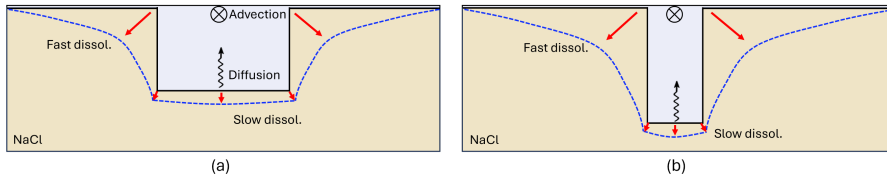


Figure 2.19. Diagram illustrating dissolution heterogeneity along the depth direction; left and right panels show the initial G-I and G-II fracture geometries, respectively.

The influence of fracture geometry on dissolution mass and rate is assessed in terms of the available reactive surface area. Compared to samples S1–S4 with G-I fracture geometry, samples S5–S8 with G-II fracture geometry consistently show a higher overall dissolution mass under identical fluid conditions (Figure 2.11, Figure 2.12 and Figure 2.13). This is attributed to differences in the initial fracture surface area: the G-II geometry has a larger initial fracture surface area ($10,600 \text{ mm}^2$) than the G-I geometry ($7,920 \text{ mm}^2$). A comparison of samples S2, S6, and S10 under identical fluid conditions further supports this trend, with S6 exhibiting significantly greater dissolution due to its larger reactive surface (Figure 2.20 (a)). These observations align with previous findings that greater dissolution area generally leads to increased fluid–rock interaction sites (James & R Lupton, 1978). Flow-through experiments by Fairchild et al. (1999) and Sadeghiamirshahidi & Vitton, (2019)) also show a direct correlation between surface area exposure and dissolution rate. Additionally, the difference in dissolution mass between the G-I and G-II geometries decreases as salt concentration and flow rate increase (Figure 2.20 (b)). At lower flow rates, longer residence times allow sustained reactions at the fluid–rock interface, while lower concentrations promote dissolution rate, thereby enhancing dissolution kinetics until the available reaction surface area becomes the primary limiting factor. As flow rate increases, the system shifts from a surface-controlled to a transport-controlled regime, as the reduced residence time limits the extent of reaction.

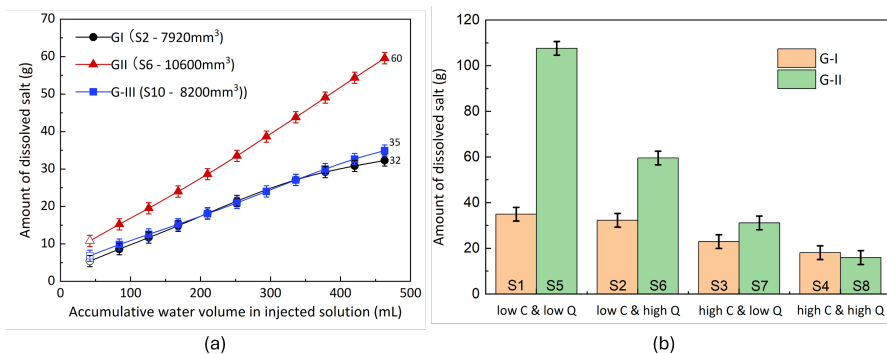


Figure 2.20. (a) Dissolution mass versus accumulated water volume in the injected solution for S2, S6, and S10; (b) Dissolution mass of samples S1–S8.

2.4.2 Effect of fluid conditions

Although the same total fluid volume is injected in all experiments, the evolution of dissolution area, dissolution mass, and dissolution rate, as well as the simulation results, consistently follows the sequence $S1 > S2 > S3 > S4$ for G-I geometries and $S5 > S6 > S7 > S8$ for G-II geometries (Figure 2.11, Figure 2.12, and Figure 2.18). At lower flow rates (e.g., $S1$ vs. $S2$, $S5$ vs. $S6$), increased residence time within the fracture allows more extensive fluid–rock interactions, resulting in greater dissolution mass. This effect is further enhanced under conditions of lower salt concentration, which create a higher concentration gradient. Additionally, under conditions of low flow rate (2 mL/min) and high salt concentration (300 g/L, $S9$), attempts to induce precipitation are unsuccessful, as continuous advective transport prevented the system from reaching the required supersaturation state. This observation underscores the competitive interplay between reaction kinetics and advective transport in controlling dissolution behaviour. Specifically, when surface reaction kinetics outpace advective removal of dissolved ions, dissolution proceeds vigorously. Rapid fluid flow flushes solutes away promptly, thereby limiting the extent of further reaction ($S3$, $S4$, $S7$ and $S8$). Additionally, flow rates below 0.01 mL/min produce a slowly advancing dissolution front, while salt re-precipitation causes clogging and, in some cases, complete flow cessation within the cores (Weisbrod et al., 2012). In this study, the applied flow rates (3 and 9 mL/min) prevent re-precipitation. Therefore, under flowing conditions in an open system, where continuous fluid exchange with the surroundings is maintained via a source and sink, precipitation is unlikely to occur at the decimetre scale.

Moreover, the influence of salt concentration and flow rate on fracture geometry evolution has been studied. The dimensionless Péclet (Pe) and Damköhler (Da) numbers are used to capture the balance between transport and reaction kinetics. As the Pe number increases, the dissolution regime typically transitions from a wedge-shaped pattern, where dissolution remains localized near the inlet, to a more uniform dissolution state, where reactions are distributed more evenly throughout the domain (Deng & Spycher, 2019; Zhou et al., 2022). However, no clear transition in geometric evolution is observed in this study, based on the dissolution regimes in the Pe–Da number space (see Figure 2.21), with the calculation process detailed in Appendix A8. This is likely because previous studies have focused on relatively homogeneous and predominantly two-dimensional systems (Menke et al., 2023; Zhou et al., 2022). In contrast, the simplified 3D fracture networks examined here introduce complexities that deviate from the classical Pe–Da framework, highlighting the need for further investigation or the development of new quantification standards. Nevertheless, based on dissolution mass, lower Péclet numbers and higher Damköhler numbers generally correspond to greater dissolution in this study.

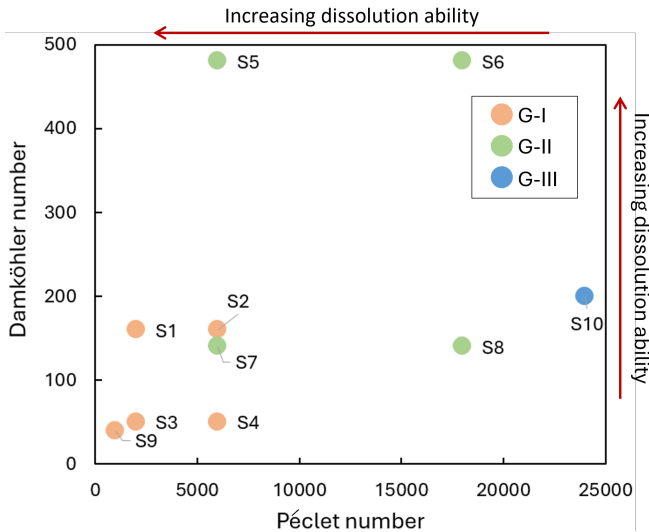


Figure 2.21. Dissolution regimes in the Péclet number-kinetic number space

2.4.3 Implications

During leaching, the damaged zone around salt cavern wall is exposed to undersaturated solutions, triggering progressive fracture enlargement through dissolution processes (Elkhoury et al., 2015; Renshaw et al., 2020). Dissolution within the fractures is inherently uneven, with preferential removal of material near the inlet and along fracture edges. This leads to increased fracture aperture and enhanced permeability within the damage zone. Fractures with larger reactive surface areas tend to dissolve more rapidly, and the development of interconnected fracture networks can further amplify reactive surface availability, accelerating mass loss and potentially threatening the long-term integrity of the salt cavern. However, increase fluid velocity and solute concentration can mitigate the effect of surface area variability on dissolution mass.

Fracture surface evolution exhibits a smoothing tendency, enhancing dissolution in advection-dominated zones while suppressing it in areas governed by diffusion. This smoothing is particularly evident under low flow rates and dilute conditions, where extended fluid–rock interaction promotes gradual levelling of rough features. In contrast, elevated flow rates and high solute concentrations help preserve the initial geometry by limiting the residence time of reactive fluids. As such, controlling flow velocity is crucial for regulating fracture evolution during leaching operations and for maintaining the mechanical stability of the salt formation. In such scenarios, numerical modelling offers a valuable tool to investigate the position of the saturation front and the coupled dynamics of dissolution, transport, and precipitation.

2.5 Conclusions

In this study, we investigate how initial fracture geometry, salt concentration, and flow rate influence the evolution of rock salt fracture channels. To achieve this, we developed a flow-visualization experimental setup combined with quantitative measurement techniques. The main findings are as follows:

(1) Dissolution within rock salt channels is highly heterogeneous, with increased dissolution near the inlet and along fracture corners due to advection-dominated flow, leading to progressive smoothing of fracture surfaces. Fractures with larger initial surface areas exhibit higher dissolution rates and greater total mass loss compared to those with smaller surfaces. This difference narrows as fluid flow rate and concentration increase, indicating that transport conditions moderate the influence of surface area.

(2) Lower salt concentrations and flow rates enhance dissolution in this decimetre-scale experimental model. However, the resulting patterns do not consistently conform to the conventional Péclet (Pe)–Damköhler (Da) framework observed in micro-scale studies, suggesting scale-dependent deviations in reactive transport behaviour. This highlights the need to extend existing dimensionless frameworks when applied at larger scales, where additional factors such as evolving fracture geometry, longer transport paths, and flow heterogeneity play a more dominant role.

2.6 References

- Al-Khulaifi, Y., Lin, Q., Blunt, M. J., & Bijeljic, B. 2018. Reservoir-condition pore-scale imaging of dolomite reaction with supercritical CO₂-acidified brine: Effect of pore-structure on reaction rate using velocity distribution analysis. *International Journal of Greenhouse Gas Control*, 68, 99–111. <https://doi.org/10.1016/j.ijggc.2017.11.011>
- Daccord, G., Lenormand, R., & Lietaud, O. 1993. Chemical dissolution of a porous medium by a reactive fluid—I. Model for the “wormholing” phenomenon. *Chemical Engineering Science*, 48(1), 169–178. [https://doi.org/10.1016/0009-2509\(93\)80293-Y](https://doi.org/10.1016/0009-2509(93)80293-Y)
- Deng, H., & Spycher, N. 2019. Modeling reactive transport processes in fractures. *Reviews in Mineralogy and Geochemistry*, 85(1), 49–74. <https://doi.org/10.2138/rmg.2019.85.3>
- Detwiler, R. L. 2008. Experimental observations of deformation caused by mineral dissolution in variable-aperture fractures. *Journal of Geophysical Research: Solid Earth*, 113(8). <https://doi.org/10.1029/2008JB005697>
- Detwiler, R. L., & Rajaram, H. 2007. Predicting dissolution patterns in variable-aperture fractures: Evaluation of an enhanced depth-averaged computational model. *Water Resources Research*, 43(4). <https://doi.org/10.1029/2006WR005147>
- Detwiler, R. L., Glass, R. J., & Bourcier, W. L. 2003. Experimental observations of fracture dissolution: The role of Peclet number on evolving aperture variability. *Geophysical Research Letters*, 30(12). <https://doi.org/10.1029/2003GL017396>
- Dijk, P. E., Berkowitz, B., & Yechieli, Y. 2002. Measurement and analysis of dissolution patterns in rock fractures. *Water Resources Research*, 38(2), 5–15–12. <https://doi.org/10.1029/2001WR000246>
- Durham, W. B., Bourcier, W. L., & Burton, E. A. 2001. Direct observation of reactive flow in a single fracture. *Water Resources Research*, 37(1), 1–12. <https://doi.org/10.1029/2000WR900228>
- Durie, R. W., & Jessen, F. W. 1964. Mechanism of the dissolution of salt in the formation of underground salt cavities. *Society of Petroleum Engineers Journal*, 4(02), 183–190. <https://doi.org/10.2118/678-PA>
- Durie, R.W. and Jessen, F.W., 1964. The influence of surface features in the salt dissolution process. *Society of Petroleum Engineers Journal*, 4(03), pp.275–281. <https://doi.org/10.2118/1005-PA>
- Dutka, F., Starchenko, V., Osselin, F., Magni, S., Szymczak, P., & Ladd, A. J. C. 2020. Time-dependent shapes of a dissolving mineral grain: Comparisons of simulations with microfluidic experiments. *Chemical Geology*, 540. <https://doi.org/10.1016/j.chemgeo.2019.119459>
- Elkhoury, J. E., Detwiler, R. L., & Ameli, P. 2015. Can a fractured caprock self-heal? *Earth and Planetary Science Letters*, 417, 99–106. <https://doi.org/10.1016/j.epsl.2015.02.010>
- Fairchild, I. J., Killawee, J. A., Hubbard, B., & Dreybrodt, W. 1999. Interactions of calcareous suspended sediment with glacial meltwater: A field test of dissolution behaviour. *Chemical Geology*, 155(3–4), 243–263. [https://doi.org/10.1016/S0009-2541\(98\)00170-3](https://doi.org/10.1016/S0009-2541(98)00170-3)
- James, A. N., & Lupton, A. R. 1978. Gypsum and anhydrite in foundations of hydraulic structures. *Géotechnique*, 28(3), 249–272. <https://doi.org/10.1680/geot.1978.28.3.249>
- Kanagawa, K., Cox, S. F., & Zhang, S. 2000. Effects of dissolution–precipitation processes on the strength and mechanical behavior of quartz gouge at high-temperature hydrothermal conditions. *Journal of Geophysical Research: Solid Earth*, 105(B5), 11115–11126. <https://doi.org/10.1029/2000JB900038>
- Koch, P. 2008. Equivalent diameters of rectangular and oval ducts. *Building Services Engineering Research and Technology*, 29(4), pp.341–347. <https://doi.org/10.1177/0143624408094631>
- Ladd, A. J., & Szymczak, P. 2021. Reactive flows in porous media: Challenges in theoretical and numerical methods. *Annual Review of Chemical and Biomolecular Engineering*, 12(1), 543–571. <https://doi.org/10.1146/annurev-chembioeng-092920-102703>
- Ling, D., Zhu, S., Zheng, J., Xu, Z., Zhao, Y., Chen, L., Shi, X., & Li, J. 2023. A simulation method for the dissolution construction of salt cavern energy storage with the interface angle considered. *Energy*, 263. <https://doi.org/10.1016/j.energy.2022.125792>
- Menke, H. P., Maes, J., & Geiger, S. 2023. Channeling is a distinct class of dissolution in complex porous media. *Scientific Reports*, 13(1). <https://doi.org/10.1038/s41598-023-37725-6>
- Menon, E.S., 2015. Fluid flow in pipes. *Transmission pipeline calculations and simulations manual*, pp.149–234. <https://doi.org/10.1016/B978-1-85617-830-3.00005-5>
- Noiriel, C., & Deng, H. 2018. Evolution of planar fractures in limestone: The role of flow rate, mineral heterogeneity and local transport processes. *Chemical Geology*, 497, 100–114. <https://doi.org/10.1016/j.chemgeo.2018.08.026>
- Renshaw, C. E., Schulson, E. M., Iliescu, D., & Murzda, A. 2020. Increased fractured rock permeability after percolation despite limited crack growth. *Journal of Geophysical Research: Solid Earth*, 125(8). <https://doi.org/10.1029/2019JB019240>
- Sadeghiamirshahidi, M., & Vitton, S. J. 2019. Laboratory study of gypsum dissolution rates for an abandoned underground mine. *Rock Mechanics and Rock Engineering*, 52(7), 2053–2066. <https://doi.org/10.1007/s00603-018-1696-6>
- Song, W., Ogunbanwo, F., Steinsbø, M., Fernø, M. A., & Kovscek, A. R. 2018. Mechanisms of multiphase reactive flow using biogenically calcite-functionalized micromodels. *Lab on a Chip*, 18(24), 3881–3891. <https://doi.org/10.1039/C8LC00793D>
- Villamor-Lora, R., Germaine, J. T., & Einstein, H. H. 2023. Experimental investigations of fracture deformation, flow, and transport using a pressure-controlled Hele-Shaw cell and digital fabrication. *Water Resources Research*, 59(8), e2022WR032290. <https://doi.org/10.1029/2022WR032290>
- Wang, T., Hu, R., Yang, Z., Zhou, C. X., Chen, Y. F., & Zhou, C. B. 2022. Transitions of dissolution patterns in rough fractures. *Water Resources Research*, 58(1). <https://doi.org/10.1029/2021WR030456>
- Weisbrod, N., Alon-Mordish, C., Konen, E., & Yechieli, Y. 2012. Dynamic dissolution of halite rock during flow of diluted saline solutions. *Geophysical Research Letters*, 39(9). <https://doi.org/10.1029/2012GL051306>
- Zhou, C. X., Hu, R., Li, H. W., Yang, Z., & Chen, Y. F. 2022. Pore-scale visualization and quantification of dissolution in microfluidic rough channels. *Water Resources Research*, 58(11). <https://doi.org/10.1029/2022WR032255>

3. Fracture healing and surface roughness evolution in rock salt

Abstract: Constructing repositories in rock salt may induce fractures that act as mechanical weakness. Laboratory and field studies show that rock salt can regain strength over time (i. e., healing process), but little data exist regarding long-term (>weeks) strength recovery of rock salt fractures. In this study, we investigate the shear strength recovery and sliding behaviour in a two-step process where rock salt samples with healed artificial fractures allowed to heal up to one year under dry or wet (saturated brine) conditions are then used in constant displacement shear box tests. To obtain a Mohr-Coulomb type criterion during slip, normal stresses of approximately 55, 109, 218, 436, and 872 kPa are applied. Mechanical recovery follows a log-linear relationship with healing time under both dry and wet conditions, with recovery in wet samples reaching up to seven times that of dry samples. We infer strength recovery can be attributed to plastic flow induced by dislocation in dry samples, whilst in wet samples additional mechanisms occur, most likely to be pressure solution, recrystallisation, and possibly surface energy minimisation. The evolution of fracture surface geometry is examined before healing and after shearing using microcomputed tomography and digital microscopy. Healing modifies the surface topography, resulting in rougher fracture surfaces, which results in stick slip behaviour during sliding for all samples, where dry samples show 3 to 10 times higher event frequency and 3 to 5 times lower stress drop compared to wet samples. The residual friction angle increases with healing time in dry samples, while remaining constant in wet samples. The differences in stick-slip behaviour between dry and wet samples are interpreted in terms of the dominance of distance-dependent stick-slip mechanisms under dry conditions versus velocity-dependent mechanisms under wet conditions.

3.1 Introduction

Subsurface energy storage plays a vital role in addressing major societal challenges by enhancing supply security and supporting the energy transition, particularly through the storage of natural gas, hydrogen, and compressed air (Istvan et al., 1997; King et al., 2021; Williams et al., 2022). Salt rock is also regarded as a potential medium to dispose radioactive waste. This can all be attributed to salt rock's low porosity (<1%), extremely low permeability (<10⁻²⁰ m²), relatively high ductility and large rock volumes (Urai & Spiers et al., 1986; Stormont & Daemen., 1992; Peach & Spiers., 1996; Hunsche & Hampel., 1999; Houben et al., 2013; Blanco-Martín et al., 2022). However, as a result of excavation, the salt rock surrounding openings experiences mechanical, hydraulic, and geochemical alterations, leading to the formation of a so-called damaged or disturbed zone (Tsang et al., 2005). Fractures in that damage zone can serve as mechanical weakness or preferential pathways for the migration of pollutants, posing significant challenges to the safety, sustainability, and cost-effectiveness of salt cavern storage sites and repositories. On the positive side, salt rock has excellent healing properties, which contribute to the recovery of intact material properties and enhance the overall structural integrity and safety of underground projects (Costin & Wewersik., 1980; Brodsky & Munson., 1994; Salzer et al., 2007). Therefore, it is crucial to understand the long-term healing process of rock salt fractures, i.e. the evolution of the mechanical properties of fractures in rock salt over time.

Over the past few decades, extensive research has focused on the healing properties of damaged rock salt. These studies have evaluated the effects of various healing conditions on the damage degree, permeability, and recovery of strength, as reflected by tensile strength, friction coefficient, and cohesion in rock specimens or simulated fracture and fault gouge samples, highlighting the influence of confining pressure (Costin & Wewersik., 1980; Brodsky et al., 1990; Fuenkajorn & Phueakphum., 2011), temperature (Brodsky & Munson., 1994), healing time (Brodsky et al., 1990; Brodsky & Munson., 1994; Li et al., 2024), initial damage (Chan et al., 1994), fluid composition (Bos et al., 2000; Chen et al., 2013), and fracture surface morphology (Fuenkajorn & Phueakphum., 2011). Costin & Wewersik (1980) examined the healing properties of rock salt using pre-damaged samples. This demonstrated that, under confining pressures of 10 to 35 MPa and temperatures between 22 and 100 °C, the fracture toughness of the specimens recovered to approximately 70 to 80% of their original values. Sustaining elevated pressures for up to five days can result in complete fracture closure and healing, as indicated by compressional wave ultrasonic measurements (Brodsky et al., 1990; Brodsky & Munson., 1994). However, these experiments have a large uncertainty, and no conclusive statement could be made about the proportion of closed fractures that not only sealed (i.e. permeability reduction) but also healed (i.e. strength regain). Fuenkajorn & Phueakphum (2011) studied the effect of fracture types, including tension-induced fractures versus saw-cut versus smooth polished fractures on healing of rock salt fractures. They found that healing largely depends on the origin of the fracture geometry. Fractures formed by the separation or splitting of salt crystals can heal readily, even under relatively low stress of 0.69 MPa within a short period of five days. Li et al. (2024) employed the Brazilian splitting test to assess tensile strength recovery in healed rock salt fractures under both dry and wet conditions. The results showed that the presence of a solution significantly accelerates the healing process, whereas no measurable

healing occurred in the dry samples in the investigated time span. Chen et al. (2013) investigated the effects of initial damage, temperature, humidity, and solution composition on the healing process of damaged rock salt using ultrasonic technology in conjunction with triaxial testing. Salzer et al. (2007) conducted direct shear tests between the surfaces of dry or wet salt bricks and used the Mohr-Coulomb criterion to describe the mechanical properties of the discontinuity plane. Significant strengthening was observed when moisture was present because of the development of cohesion. Bos et al. (2000) conducted slide-hold-slide (SHS) experiments on synthetic faults containing granular halite gouge, using NaCl-saturated mixtures of water and methanol as pore fluids, to investigate the effects of pore fluid composition and gouge grain size on slip behaviour. Regular stick-slip events were observed, and the friction coefficient in dry samples was shown to be lower than in wet samples. They proposed that pressure solution can promote densification and strengthening, leading to brittle-frictional behaviour. Slide-Hold-Slide (SHS) experiments were also performed on simulated quartz or salt fault gouge, with many studies showing that longer hold periods result in a larger static friction coefficient and a general increase in shear strength upon subsequent loading (Karner et al., 1997; Olsen et al., 1998; Kanagawa et al., 2000; Nakatani & Scholz, 2004; Hunfeld et al., 2020; Niemeijer et al., 2022). The friction increase generally follows a linear-logarithmic relationship with holding time, in accordance with Dieterich's law (Dieterich, 1972; Dieterich, 1994). For reactive materials, a power-law relationship may offer a more accurate fit (Renard et al., 2012; Pluymakers and Niemeijer, 2015). These studies on simulated gouges primarily focus on investigating strength recovery in faults between earthquake events (Karner et al., 1997; Kanagawa et al., 2000; Niemeijer et al. 2008; Renard et al., 2012; Pluymakers and Niemeijer, 2015).

In addition to studying the evolution of mechanical properties, research has also focused on the reduction of permeability and the geometric evolution of fractures in rock salt. Many studies have indicated that the restoration of mechanical strength of fractures (healing) is inherently linked to permeability reduction (sealing) (Sutherland & Cave, 1980; Peach, 1991; Pfeifle & Hurtado, 1998; Renard et al., 2000; Tenthoirey et al., 2003; Yasuhara, 2004). Through microscale observations, underlying mechanisms behind permeability reduction and geometry evolution of fractures have been discussed. Houben et al. (2013) concluded that healing of fractures in rock salt can be attributed to three possible mechanisms: (1) mechanical closure via elastic deformation, plastic deformation or pressure solution; (2) narrowing of fractures into isolated tubular or spherical inclusions driven by surface energy and diffusion through water films or brine inclusions; and (3) closure through recrystallisation processes. The above-mentioned possible healing mechanisms would lead to changes in the evolution in the surface morphology and roughness of the fractures. Ji et al. (2022) used microtomography to study the evolution of microfracture networks in artificially damaged natural salt through brine-assisted processes. They found that rock salt fractures became crystallographically faceted, necked, discontinuous, and disconnected, producing an increase in tortuosity and a decrease in connectivity of the fracture network. Li et al. (2024) used scanning electron microscopy (SEM) to observe rapid crystal growth on rock salt fractures. The crystals grew until they touched the opposite side, causing the fracture to segment along its length. The studies mentioned above have primarily focused on specific aspects of fracture healing in rock salt, such as the evolution of physical or mechanical properties, or fracture surface morphology. However, there is a gap in research that integrates the long-term

mechanical strength recovery of rock salt fractures with the evolution of fracture surface characteristics under either dry or wet healing conditions.

To bridge the gap, we investigate the shear strength recovery of rock salt fractures in a two-step process. First, samples subjected to a normal stress under dry or wet conditions for an extended period of time, up to one year. The samples are then placed in a direct shear box and subjected to shearing under increasing normal stresses. Additionally, we study the evolution of fracture surface geometry through observations by microcomputed tomography (micro-CT) and digital microscopy. The results are analysed in terms of shear strength recovery, residual friction angle evolution, static and dynamic friction related to stick-slip behaviour and surface microstructure evolution. The effects of healing time and saturated brine presence on the mechanical recovery and surface geometry evolution of rock salt fractures, as well as the healing mechanisms under dry and wet healing conditions, are discussed.

3.2 Methodology

3.2.1 Sample preparation

The original samples are cut with a handsaw to match the shear box dimensions and manually polished with 80-grit sandpaper to ensure a uniform initial surface roughness on the fracture surfaces of the rock salt plates (Figure 3.1 (a)). The samples are then assembled by placing one plate on top of another of the same dimensions, each measuring 60 ± 0.5 mm in length, 60 ± 0.5 mm in width, and 14 ± 0.2 mm in depth (Figure 3.1 (b)). The space between the fracture surfaces of the two rock salt plates represents the fracture gap (Figure 3.1 (c)). Before static compaction, the microstructure of the fracture surfaces is analysed using a digital microscope (Keyence VHX-7000).

To trigger healing of the samples under relatively dry conditions (i.e., drier than ambient air), two plates are placed inside a sealed double zip lock bag, with the inner bag containing five sachets of silica gel desiccant. This prevents the fracture surfaces of the rock salt from absorbing too much moisture from the air, thereby maintaining the fracture in a steady state of low-humidity ("dry") conditions relative to the ambient air (approximately 3 to 8 ppm) (Ravelli et al., 2022) (Figure 3.2 (a)). For samples under wet healing conditions, the plates are fully immersed in a saturated brine solution, which is prepared from crushed material of the original rock salt block (Figure 3.2 (b)). A 20 kg load, equivalent to a normal stress of 54 kPa, is applied to the top of the samples outside the zip lock bags for durations of up to 373 days. All experiments are listed in Table 3.1.

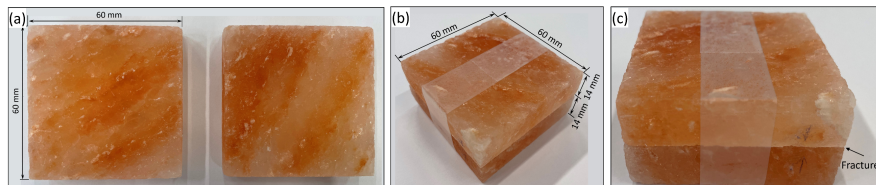


Figure 3.1. The dimensions of the rock salt plates used in the shear box tests are depicted in (a) and (b), with (c) showing the gap that simulates the fracture. The visible band represents the sellotape holding the rock salt plates together, which will be removed prior to shearing.

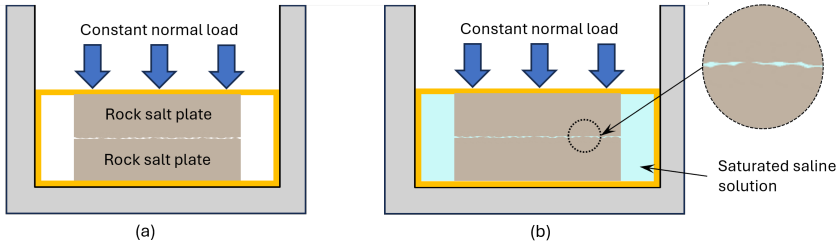


Figure 3.2. (a) and (b) depict the sample healing process under either dry or wet conditions, respectively. The yellow rectangle represents a plastic barrier that isolates the compaction system from the environment, preventing air intrusion and solution evaporation.

Table 3.1. List of experiments and results presented in this study. The test samples are labelled as follows: "D" or "W" indicates dry or wet healing conditions, "TXXX" specifies the healing time in days, and "A" or "B" denotes replicate samples.

Exp.	Healing condition	Healing time (Days)	Healing strength/ τ_H (kPa)	Healing strength recovery/ τ_{re} (kPa)	Average recovery rate / $\dot{\tau}_{re}$ (kPa/days)	Residual Friction angle/ $\phi(^{\circ})$
D-T000	Dry	0*	15.5	-	-	5.4 – 14.9
D-T017	Dry	17	18.2	2.7	0.159	6.5 – 14.5
D-T042	Dry	42	22.3	6.8	0.162	11.6 – 21.2
D-T115	Dry	115	27.8	12.3	0.107	9.2 – 23.3
D-T192	Dry	192	31.0	15.5	0.082	6.8 – 27.3
W-T000	Wet	0*	50.9	-	-	0 – 41.5
W-T003-A	Wet	3	95.1	44.2	14.733	0 – 40.3
W-T003-B	Wet	3	126.0	75.1	25.033	-
W-T008	Wet	8	185.4	134.5	16.813	0 – 41.8
W-T017-A	Wet	17	108.0	57.1	3.359	0 – 40.5
W-T017-B	Wet	17	215.3	164.4	9.671	-
W-T042-A	Wet	42	211.3	160.4	3.819	0 – 40.0
W-T042-B	Wet	42	204.8	153.9	3.664	-
W-T115	Wet	115	250.9	200.0	2.000	0 – 43.3
W-T373	Wet	373	294.1	243.2	0.652	-

3.2.2 Direct shear box test

Direct shear box experiments are performed using an ELE INTERNATIONAL digital direct shear apparatus with a 10:1 lever loading assembly. The placement of the sample in the shear box is shown in (Figure 3.3 (a)-(d)). To ensure shearing along the salt blocks interface, two 1.6 mm-thin copper layers are glued on the boundaries parallel to the shear direction. Before conducting the test, a lubricant is applied to the copper layer surface to minimise friction between the layers and the shear box. All tests are conducted at room temperature. For both dry and wet conditions, non-healed samples (zero days of healing) are compared. Dry samples with zero days of healing are placed into the shear box without additional preparation, while wet samples with zero days of healing are immersed in a brine bath for a few minutes before shearing. Consequently, no healing

effects contribute to the shear resistance for non-healed samples, which is instead determined solely by the friction of the fracture surface. For all wet samples, the fracture surfaces are wet during the shear experiment, since they are transferred directly from the saturated brine, and shearing is initiated within minutes after removal from the static loading configuration. The samples are then sheared at a constant rate of 0.5 mm/min, consistent with values adopted in previous studies (Mirzaghobanali et al., 2014; Tang & Wong, 2016). When extracting the initially wet samples from the shear box and disassembling them to investigate the contact surfaces, they were always visibly wet. Therefore, fracture surface is wet during shear box test.

To determine the mechanical properties and friction behaviour of the rock salt fractures, the samples are sheared at a constant velocity under five stepwise normal loads. The applied normal loads are 196 N (20 kg), 392 N (40 kg), 784 N (80 kg), 1568 N (160 kg), and 3136 N (320 kg), corresponding to horizontal displacement intervals of 0–3 mm, 3–4.5 mm, 4.5–6 mm, 6–7.5 mm, and 7.5–9 mm, respectively. These five loading stages are referred to as P1, P2, P3, P4, and P5 (green curve in Figure 3.4). Given the initial contact surface area of 36 cm², the corresponding normal stresses for P1–P5 are approximately 55, 109, 218, 436, and 872 kPa. Even though each experiment generally comprises up to five stages; however, due to the maximum limitations in horizontal displacement and shear force measurement within the shear box apparatus, the wet condition experiments are limited to three or four stages.

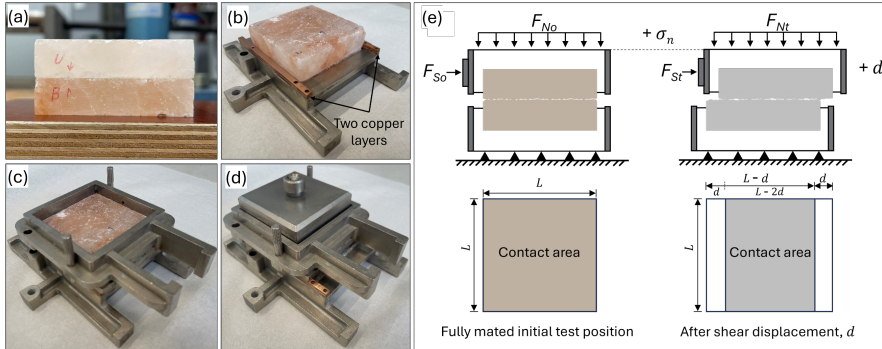


Figure 3.3. (a)–(d) show the placement of the sample in the shear device. (e) The progressively decreasing specimen contact surface area during shear test in section view and plane view.

3.2.3 Data processing

3.2.3.1 Mechanical data

3.2.3.1.1 Strength recovery

Upon shearing, the initial square-shaped contact area between the lower and upper salt rock plates reduces to a rectangular shape (Figure 3.3 (e)). Shear force (N), horizontal displacement (mm), and vertical displacement (mm) are measured on a per-second basis. Additionally, zero displacement is defined as the point when the shear box begins

operation, even though not all samples establish immediate contact. The normal stress σ_N and shear stress τ_S on the salt plates contact surface are calculated by dividing the imposed normal load F_N and measured shear force F_S by the load-bearing fracture surface area, as shown in Eq. (3.1) and (3.2) respectively.

$$\sigma_N = \frac{F_N}{L \cdot (L-d)} \quad (3.1)$$

$$\tau_S = \frac{F_S}{L \cdot (L-d)} \quad (3.2)$$

where σ_N [Pa] is the normal stress on the contact surface, F_N [N] is the normal load, L [m] is the initial length of the sample boundary d [m] is the horizontal displacement, τ_S [Pa] is the shear stress on the contact surface and F_S [N] is the shear force.

The full dataset for the shearing process in D-T000 is presented in Figure 3.4 as an example. The blue curve, representing shear stress versus horizontal displacement, shows an increase in shear stress during the P1 stage, reaching a maximum followed by an abrupt or semi-instantaneous drop. This peak shear stress observed during the P1 stage is defined as the healing strength (τ_H). Since the shear resistance in the unhealed sample arises solely from frictional behaviour without the influence of healing effects, we define the healing strength recovery (τ_{re}) as the difference between the healing strength and that of the unhealed sample (zero-healing time) under dry or wet conditions (i.e. $\tau_{re} = \tau_{H(t)} - \tau_{H(t=0)}$). Average recovery rate ($\dot{\tau}_{re}$) is calculated by dividing healing strength recovery by the healing time.

3.2.3.1.2 Friction behaviour

All experiments exhibit stick-slip behaviour during all stages; see D-T000 as example in Figure 3.4. For each loading stage, the maximum (such as the blue circles in P5, Figure 3.4) and minimum shear stress (such as the yellow circles in P5, Figure 3.4) are extracted from multiple stick-slip events within that stage. Ideally, five loading stages are conducted, each corresponding to a normal stress. The shear - normal stress relationship is then evaluated to determine the coefficient of residual friction (φ) based on Mohr-Coulomb criterion ($\tau_S = C + \sigma_N \cdot \tan \varphi$): maximum shear stresses with their corresponding normal stresses are used to determine the high residual friction angle, while minimum shear stresses are used to calculate the low residual friction angle. Note that, since this analysis focuses on the post-peak sliding behaviour, we do not focus on the cohesion. Additionally, we define the apparent friction coefficient (μ_{app}). The apparent friction coefficient, calculated as shear stress divided by normal stress on the contact surface, i.e., $\mu = \tau_S / \sigma_N$, ranges from 0 to 1.

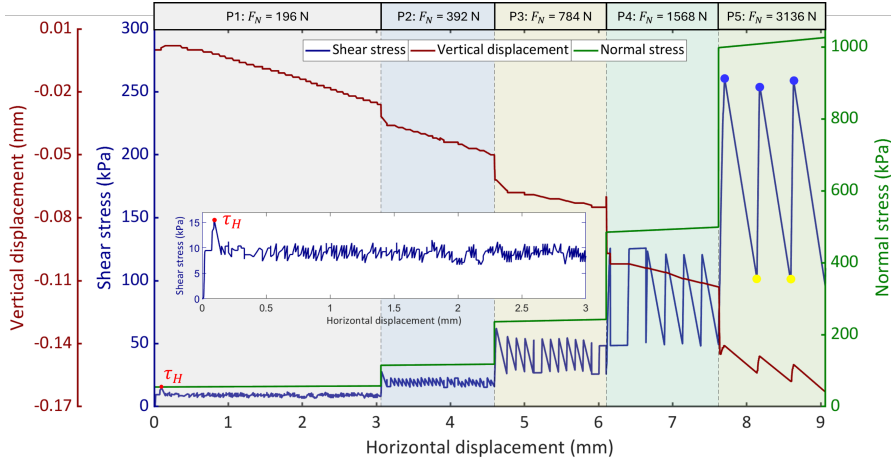


Figure 3.4. Example curves from D-T000. The blue, red, and green curves represent the relationships between shear stress, vertical displacement, and normal stress with horizontal displacement, respectively. The inset focuses on shear stress versus horizontal displacement in the P1 stage, with the red point indicating peak shear strength (τ_H).

The shear stress-displacement and shear stress-time curves in the P3 stage of D-T000 are presented in Figure 3.5 (a) and (b), respectively, showcasing multiple stick-slip events (see a zoom-in view in Figure 3.5 (c) - (d)). An individual stick-slip cycle can be divided into stick phase and slip phase. τ_{smax} and τ_{smin} denote the maximum shear stress (maximum static shear stress) and minimum shear stress (minimum dynamic shear stress) of a singular stick-slip event, and $\Delta\tau = \tau_{smax} - \tau_{smin}$ represents the stress drop. The time difference between two adjacent stick-slip events, denoted as T_R , is the recurrence interval. The frequency of stick-slip events is defined as $N = 1/T_R$ with the unit of frequency being min^{-1} . The stick-slip events are used to calculate the stress drop and frequency, as most stick-slip events exhibit similar behaviour during the same loading stage (Figure 3.5(c) - (d)).

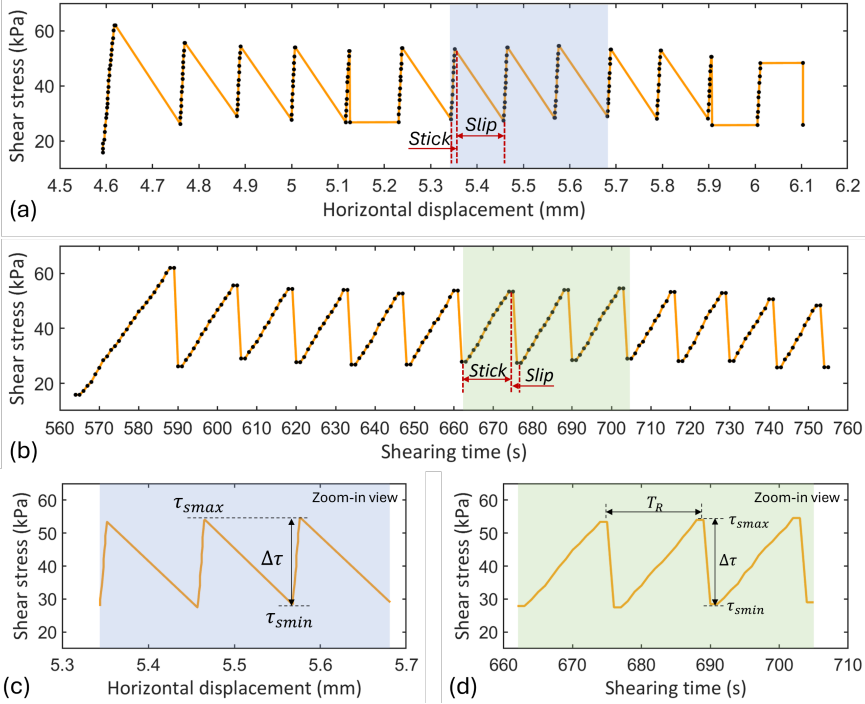


Figure 3.5. (a) Shear stress vs. horizontal displacement and (b) shear stress vs. shearing time curves for stick-slip events in P3, with black points on the yellow line marking data connections. (c) zoomed-in shear stress vs. horizontal displacement and (d) zoomed-in shear stress vs. shearing time curves for stick-slip behaviour, corresponding to the light blue and light green sections in (a) and (b), respectively.

3.2.3.2 Microstructural data

3.2.3.2.1 Digital microscope

A KEYENCE VHX-7000 digital microscope is used to compare the micro-topography of the fracture surface before static compaction with the post-shearing topography. Prior to observing, the fracture surface is meticulously cleaned using a high-pressure air gun to eliminate any potential contamination from dust or residual salt powder left over from the polishing. Some pre-healing samples are examined to assess surface characteristics. The microstructure of specific areas on the rock salt surfaces is observed at magnifications of 20x, 100x, 400x, 500x, and 1000x, using the original lens, high dynamic range (HDR) imaging, and edge enhancement features to improve the visualisation of fracture surface tomography (Figure 3.6 (a)). 3D images are obtained using the stitching function and then synthesised (Figure 3.6 (b)). Surface roughness is quantified as the root mean square roughness R_q with Keyence analysis software, based on the average of line profiles measured at two to three locations parallel to the intended shear direction. The blue line in Figure 3.6 (a) and (b) aligns with the shear direction, and the corresponding depth profile is displayed in Figure 3.6 (c). Based on measurements, R_q is calculated as:

$$R_q = \sqrt{\frac{1}{N} \sum_{i=1}^N Z_i^2} \quad (3.3)$$

where Z_i is the height deviation of each point from the mean surface, and N is total number of points measured.

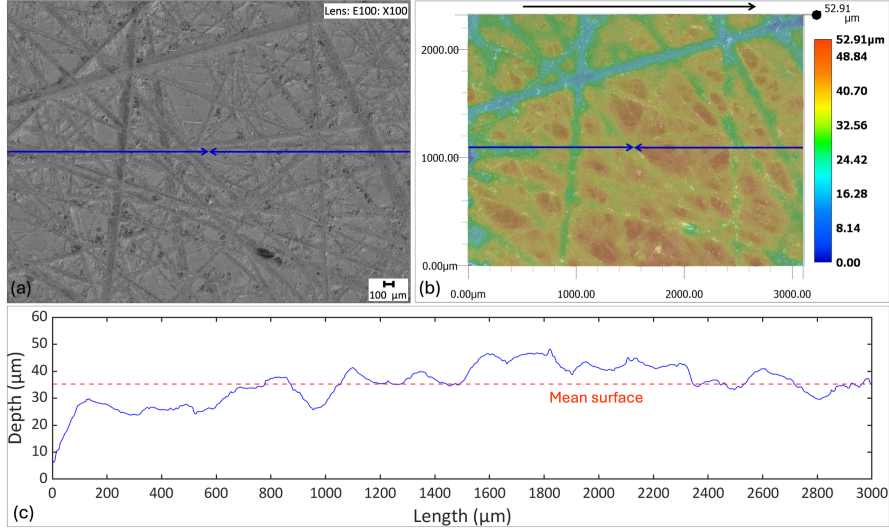


Figure 3.6. (a) and (b) show the same area of the fracture surface of D-T000 under edge-enhanced imaging and 3D imaging at 100x magnification. The black arrow in (b) indicates the intended shear direction. The blue areas represent the shallow regions, while the red areas indicate the higher regions. (c) shows the line profile corresponding to the blue line in (a) and (b).

3.2.3.2.2 Microcomputed tomography

To accurately capture both the external and internal structures of the rock salt beyond micro-observation of the fracture surface, micro-CT imaging using a TESCAN CoreTOM is performed on two samples, namely W-T042-B and W-T373 following shearing. The voxel size is 100 μm. After scanning, image reconstructions are carried out using Panthera™ software and three-dimensional models are then generated by stacking multiple slices using Avizo 2022, followed by cropping and thresholding to enhance the visibility of the rock salt sample. Surface rendering techniques are subsequently applied to visualise the 3D volume of rock salt samples.

3.3 Results

3.3.1 Mechanical results

The shear stress - horizontal displacement responses throughout the entire experiment for six representative samples are shown in Figure 3.7. The results show that the dry and

wet samples exhibit stick-slip behaviour throughout the P1 - P2 - P3 - P4 - P5 stages after reaching the peak shear stress (i.e., healing strength (τ_H)). Additionally, the stick-slip events complicate the precise adjustment of the normal load at the exact desired displacement value. For example, during the loading transition from the P3 to P4 stage, the sudden occurrence of slip makes it difficult to accurately increase the normal load at a horizontal displacement of 6 mm (Figure 3.7 (a)).

For the shear stress response during P1 stage, all dry and wet samples exhibit an initial stress peak (Figure 3.8). Prior to reaching the peak stress, dry samples show a relatively steep stress buildup, while wet samples display a more gradual build-up process (compare Figure 3.8 (a) to Figure 3.8 (b)). It should be noted that for W-T017-B and W-T042-B (indicated with a star in Figure 3.8 (b)), the stress response recordings terminate upon reaching the healing strength in the P1 stage due to a data acquisition problem, necessitating duplicate experiments (W-T017-A and W-T042-A). Furthermore, duplicate experiments for W-T003-A and W-T003-B are performed.

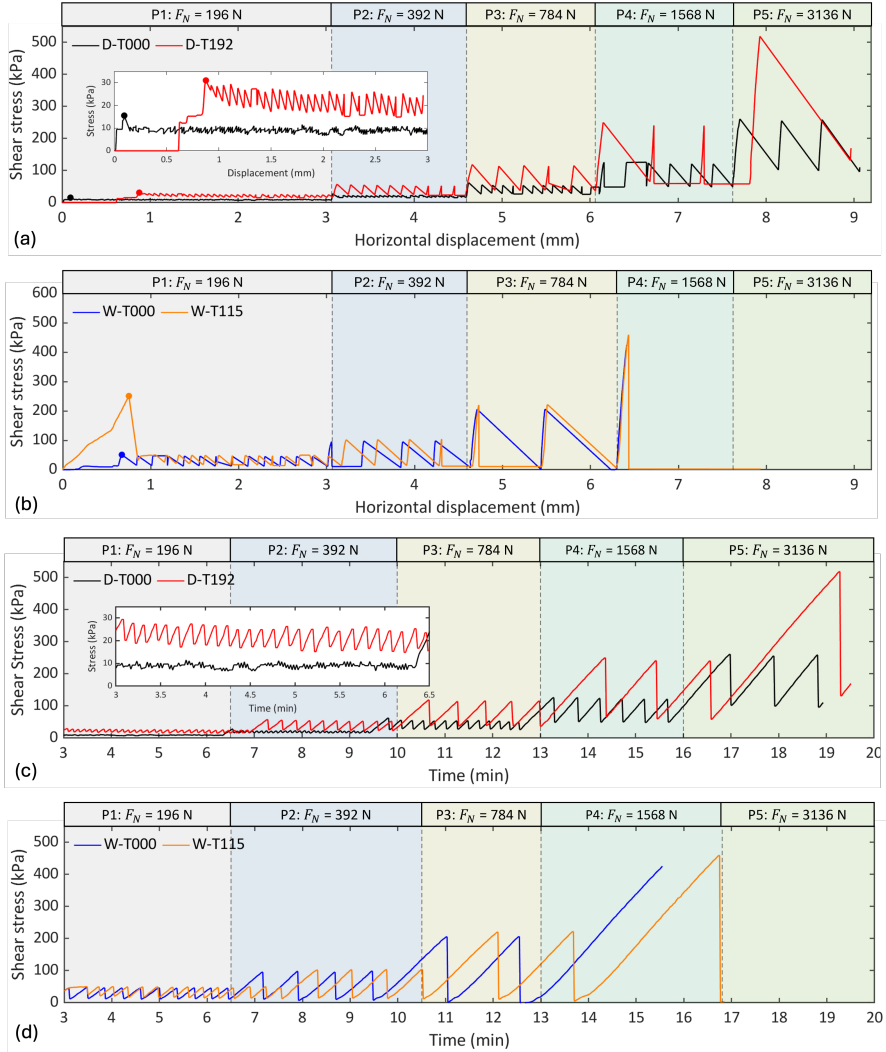


Figure 3.7. Shear stress vs. horizontal displacement for (a) D-T000 and D-T192, and (b) W-T000 and W-T115. The circle notation represents the healing strength (τ_H), which is the peak shear stress in P1 stage. Stick-slip behaviour occurs throughout all stages in all experiments. Most stick-slip events exhibit a regular sawtooth pattern in the shear stress–horizontal displacement relationship. However, the slip of some events shows a vertical drop, with shear stress remaining at a low level over a certain displacement (e.g., the shear response in the P4 stage of W-115 in (b)). This irregularity may be attributed to limitations or anomalies in the data acquisition system of the shear box during the recording of stick-slip events in terms of the stress–displacement relationship. (c) and (d) present the shear stress versus shearing time for D-T000 and D-T192 in (c), and for W-T000 and W-T115 in (d).

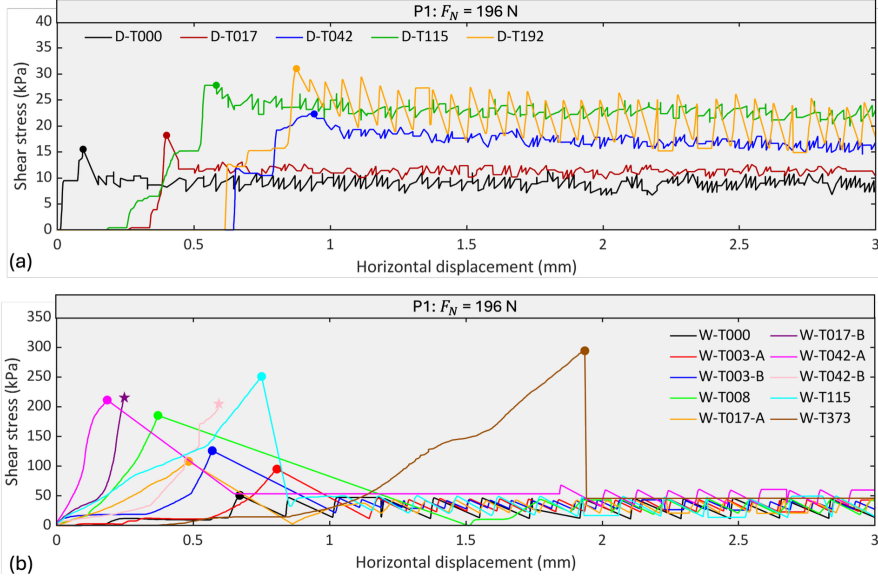


Figure 3.8. (a) and (b) shows close-ups of shear stress versus horizontal displacement in P1 for all dry and wet samples, respectively. The circle and star notations represent the healing strength (τ_H), defined as the peak shear stress in the P1 stage. The star notation indicates experiments where signal issues occurred after measuring the healing strength.

3.3.1.1 Strength recovery

Healing strength (τ_H), healing strength recovery (τ_{re}) and average recovery rate ($\dot{\tau}_{re}$) are influenced by healing time and the presence of brine (Figure 3.9). The dry unhealed sample (D-T000, 15.5 kPa) exhibits a slightly lower healing strength compared to the 17-day healed sample (D-T017, 18.2 kPa). After 192 days of dry healing, the healing strength increases to 31.0 kPa in D-T192, which is double that of unhealed sample (D-T000). The healing strength and time dependency of the wet samples far exceed those of the dry samples. The wet unhealed sample (W-T000) exhibits $\tau_H = 51$ kPa. After 42 days of wet healing, it increases to 211 kPa (W-T042-A) and 205 kPa (W-T042-B) respectively. With extended wet healing, the strength further increases to 251 kPa (W-T115) after 115 days and 294 kPa (W-T373) after 373 days (Table 3.1).

The healing strength recovery (τ_{re}) increases logarithmically with healing time for dry and wet samples (Figure 3.9 (a)). The log-linear slope for wet samples ($k = 37$ kPa/ $\lg(\text{day})$) is seven times greater than that for dry samples ($k = 5$ kPa/ $\lg(\text{day})$).

The average recovery rate decreases as healing time increases under both dry and wet conditions. For dry healed samples, the average recovery rate decreases gradually from 0.16 kPa/day for D-T017 to 0.08 kPa/day for D-T192. For wet healed samples, the most rapid decline occurs within the first 42 days, with the average recovery rate dropping sharply from 25 kPa/day (W-T003-B) to 3.7 kPa/day (W-T042-B). Beyond 115 days (W-T115 and W-T373), the average recovery rate falls below 2 kPa/day and eventually stabilises at

a plateau (Figure 3.9 (b)). Additionally, wet healed samples exhibit significantly higher average recovery rates. Even the lowest average recovery rate for wet samples (0.65 kPa/day for W-T373) is substantially greater than the highest rate for dry samples (0.159 kPa/day for D-T017). This reinforces that the presence of a saturated solution greatly enhances the average recovery rate.

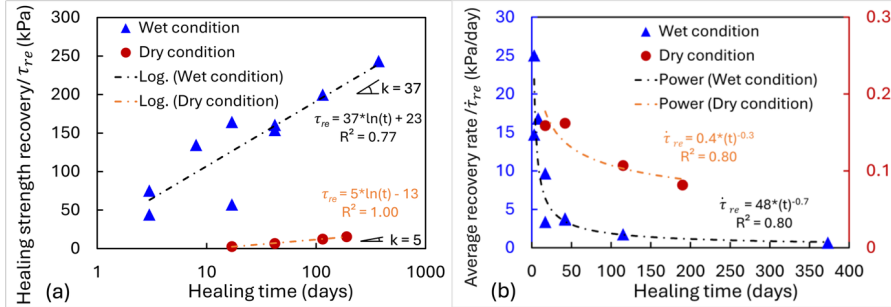


Figure 3.9. (a) Healing strength recovery (τ_{re}) as a function of healing time on a logarithmic scale, under wet and dry conditions. The value of “ k ” in (a) represents the slope of the fitting curves, the unit is kPa/lg(day). (b) Average recovery rate ($\dot{\tau}_{re}$) versus healing time.

3.3.1.2 Mohr-Coulomb parameters

For the unhealed sample (D-T000) and samples healed for 17 days, the residual friction angle ranges from 5.4° to 16.1° (low to high friction angle). After longer healing periods of 42, 115, and 192 days under dry conditions, the residual friction angle increases stepwise, clustering around 11.6° – 21.2° , 9.2° – 23.3° , and 6.8° – 27.3° , respectively, indicating a progressive increase with extended healing time. This trend is also supported by the average values of the lower and upper residual friction angles (Figure 3.10 (a) and (c)). In contrast, all wet samples exhibit residual friction angles ranging from 0° to 40.0° – 43.3° , without any clear dependence on healing duration (Figure 3.10 (b) and (c)). When comparing dry and wet conditions, the wet unhealed sample (W-T000, 0° – 41.5°) shows residual friction angles more than twice those of its dry counterpart (D-T000, 5.4° – 16.1°). Similarly, wet healed samples exhibit consistently higher residual friction angles (e.g., W-T115, 0° – 43.3°) compared to dry healed samples (e.g., D-T115, 9.2° – 23.3°), even though the overall range for wet samples remains nearly constant.

For the apparent friction coefficient in dry and wet samples (Figure 3.11), it increases with healing time in dry samples, ranging from 0.10 to 0.25 for D-T000 and from 0.12 to 0.51 for D-T192. In contrast, wet samples exhibit stronger fluctuations in the friction coefficient during stick-slip while remaining within the same range, varying from 0 to 0.85 for W-T000 and from 0 to 0.91 for W-T192.

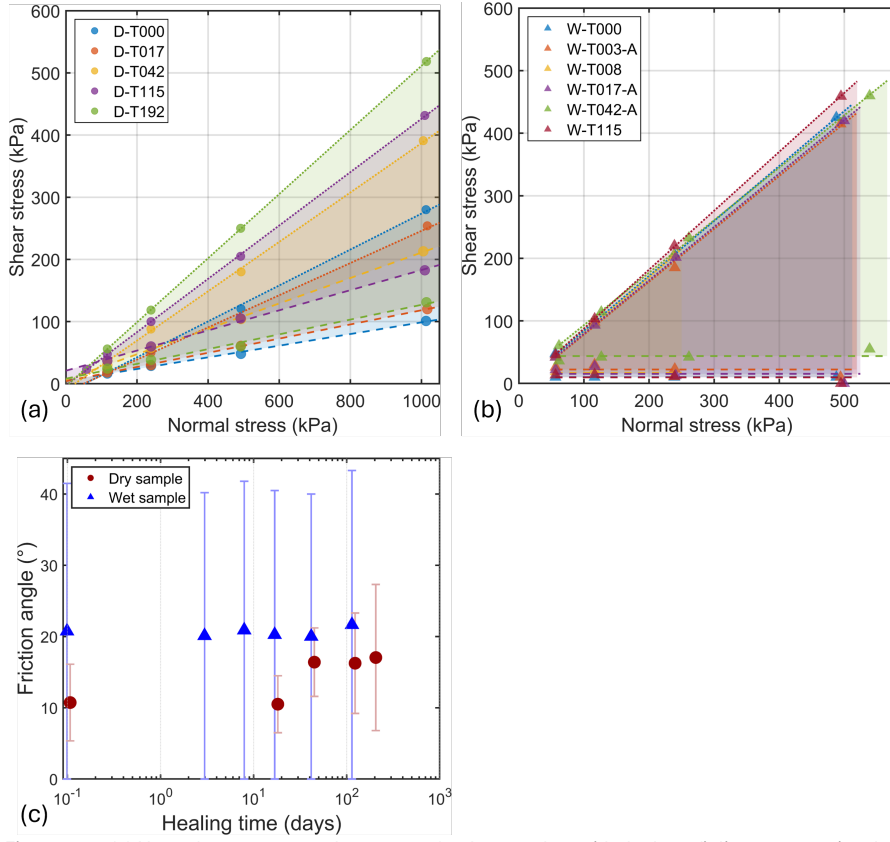


Figure 3.10. (a) Normal stress versus shear stress for dry samples, with the best-fit line representing the Mohr–Coulomb criterion ($\tau_s = C + \sigma_N \cdot \tan \varphi$). For each sample, the upper dashed line corresponds to the maximum shear stresses, while the lower dashed line (same colour) corresponds to the minimum shear stresses, both plotted against their respective normal stresses. The shaded area between the two lines indicates the range of residual friction angles. (b) Normal stress versus shear stress for wet samples. (c) Residual friction angle versus healing time for dry (red bars) and wet (blue bars) samples, showing the range between the lower and upper friction angles in (a) and (b). Red circles (dry) and blue triangles (wet) indicate the average values between the lower and upper friction angles.

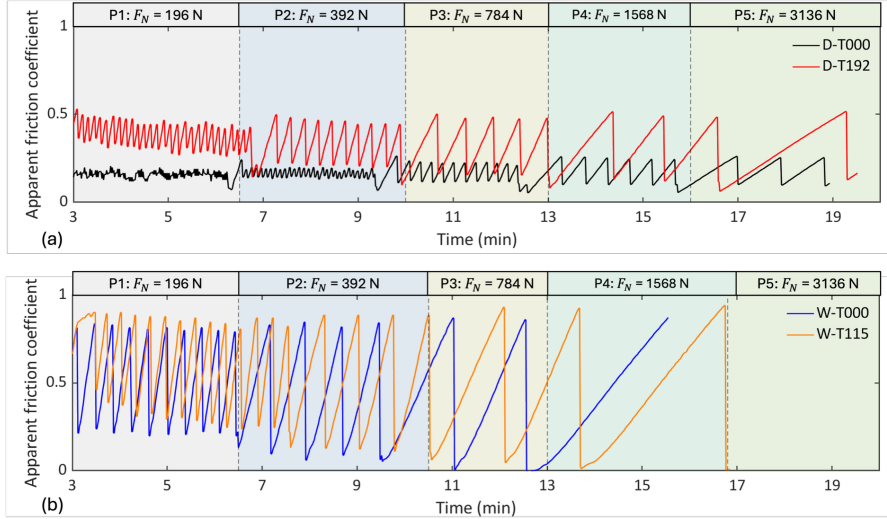


Figure 3.11. Apparent friction coefficient versus shearing time, from 3 min onward. (a) Dry tests D-T000 and D-T192, (b) W-T000 and W-T115.

3.3.1.3 Stick-slip feature

All samples exhibit stick-slip events from the P1 to P5 stages, as illustrated in Figure 3.7(c) and (d), which present the shear stress response over shearing time for two selected dry samples (D-T000 and D-T192) and two wet samples (W-T000 and W-T115). For unhealed dry samples (D-T000), stick-slip behaviour is also observed under low normal load condition (P1 stage), although the fluctuations are less regular and significantly weaker in these events. Audible acoustic emissions are produced at the moment of transition from stick to slip. Higher normal stress levels (from P1 to P5) led to louder acoustic emissions, which qualitatively correlate with larger stress drops during stick-slip events. Additionally, for both dry and wet samples, τ_{smax} and τ_{smin} increase with each successive stage from P1 to P5 (Figure 3.12 (a)). However, for wet samples, while τ_{smax} increases with higher normal loading, τ_{smin} remains consistently low (nearly zero) across all stages (Figure 3.7 (b)).

The stress drop progressively increases from P1 to P5 in all dry and wet experiments (Figure 3.12 (a) and (c)). Concurrently, the frequency of stick-slip events decreases as the stress drop increases from P1 to P5 (Figure 3.12(b) and (d)). For dry samples, the stress drop increases and the frequency of stick-slip events decreases with healing time when compared to the corresponding same loading stage. In the healed samples (D-T192), the stress drops during stick-slip events are 6-2 times greater than those in the dry, unhealed sample (D-T000), especially at low stresses (Figure 3.12 (a)). In contrast, the frequency of stick-slip events is also times higher in the dry, unhealed sample (D-T000) compared to the healed sample (D-T192). All wet samples exhibit identical stick-slip behaviours in terms of stress drop and frequency (Figure 3.12 (c) and (d)). When comparing unhealed dry and wet samples, the stress drop in the wet sample (W-T000) is eight times greater

than in the dry sample (D-T000), while the frequency of stick-slip events in the dry sample (D-T000) is times higher than in the wet sample (W-T000).

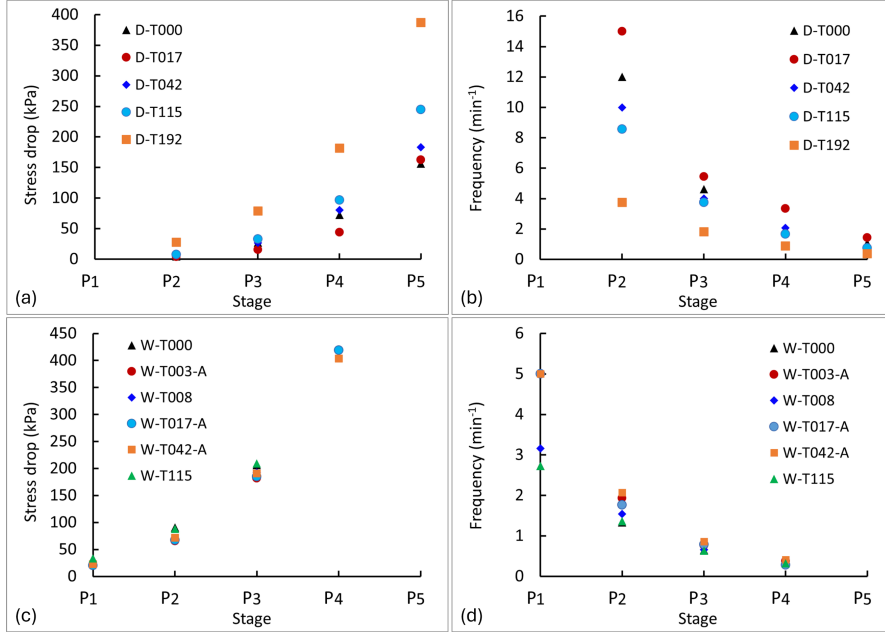


Figure 3.12. Panels (a) and (b) present the stress drops and frequencies of stick-slip behaviour for dry samples. In this case, the fluctuations in P1 stage are not considered true stick-slip events, so the stress drop and frequency are not summarised. Panels (c) and (d) display the corresponding data for wet samples.

3.3.2 Microstructural results

3.3.2.1 Fracture surface roughness

The 3D profiles of the fracture surfaces obtained using a digital microscope are presented in Figure 3.13. Additional images of some samples before healing, captured at whole-view and 20 $\times$, 400 $\times$, 500 $\times$, and 1000 $\times$ magnifications, are provided in Appendix B. The fracture surfaces before shearing exhibit uneven topography with visible scratches resulting from sanding paper (Figure 3.13 (a) and (d)). After healing and shearing, the 3D profiles of the fracture surfaces in dry samples appear similar to those of unhealed samples (Figure 3.13 (b)-(c)). In contrast, wet-healed samples show a diminishing appearance of scratches (Figure 3.13 (e)-(f)). Notably, after 373 days of wet healing, the surface exhibits isolated and disconnected elevated regions, highlighted in red in Figure 3.13(f). Quantitatively, we examine the line roughness (R_q) of the fracture surface along the shear direction before healing and after shearing (Figure 3.14). After shearing, the roughness increases in both dry and wet samples compared to the pre-shearing

condition. Additionally, the roughness of the fracture surface shows an overall upward trend with increasing healing time.

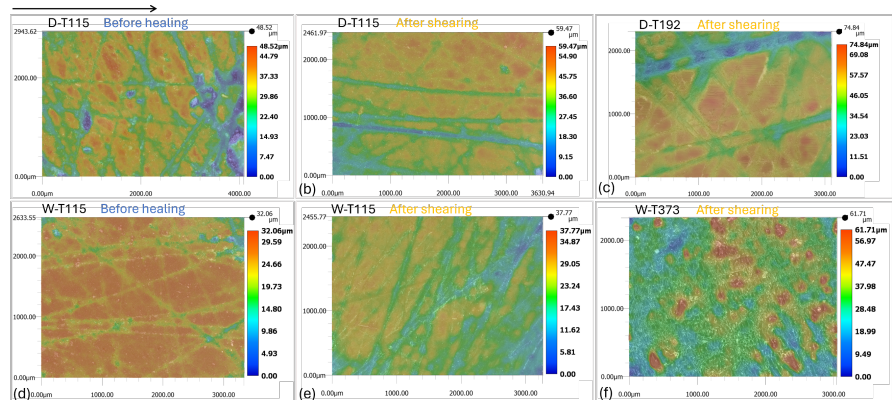


Figure 3.13. (a) and (b) show 3D images of D-T115 fracture surfaces before healing and after shearing, respectively. (d) and (e) present W-T115 before healing and after shearing. (c) and (f) depict D-T192 and W-T373 fracture surfaces after shearing. All images are captured with a 100× magnification lens, and the arrow indicates the shearing direction.

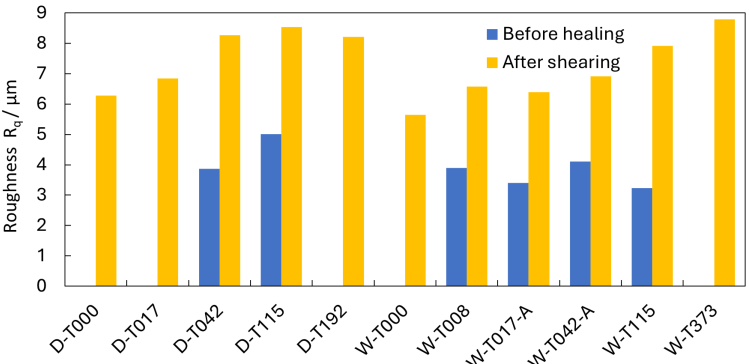


Figure 3.14. The roughness of different samples is presented; however, roughness is not measured before healing for D-T000, D-T017, D-T192, W-T000 and W-T373.

3.3.2.2 Surface geometry features

After direct shear testing, slip-parallel striations with a depth of 2-3 μm are observed exclusively on the fracture surfaces of dry-healed samples. They are easily distinguishable from scratches produced during the polishing process in sample preparation (Figure 3.15 (a)-(c)), which exhibit a depth approximately 20 μm. For wet healed samples, there also is a clear evolution in the surface microstructure. For W-T042-

B, the fracture surface initially displays arbitrary scratches caused by the polishing process prior to healing (Figure 3.16 (a)). After shearing, crystal growth with a nearly square-shaped pattern is observed on the surfaces of both halves of the shear box samples, with the extent of crystallisation varying throughout the sample (Figure 3.16 (b)). Moreover, when comparing surfaces from samples that experienced different healing times (Figure 3.17), it is clear that the size of rock salt crystals increases with extended healing durations. After 17 days of wet healing, a scaly pattern emerges on the fracture surface of W-T017-B, with crystal sizes measuring approximately $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$ (Figure 3.17 (c)). The crystals continue to grow as the healing time increases, and for W-T373, the crystal surface size reaches approximately $287\text{ }\mu\text{m} \times 291\text{ }\mu\text{m}$ (Figure 3.17 (f)), nearly 30 times larger than those observed in W-T017-B.

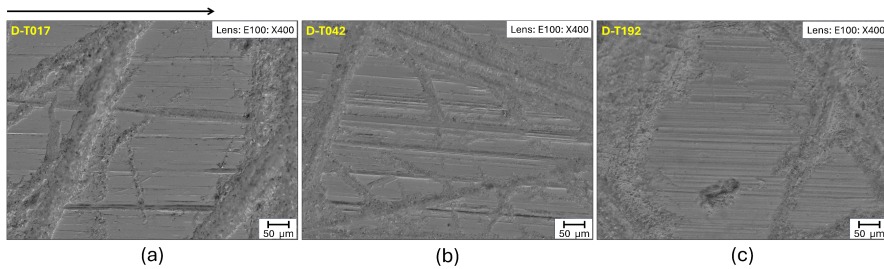


Figure 3.15. (a), (b), and (c) are edge-enhanced images at 400x magnification, showing finer and smaller scratches on samples D-T017, D-T042, and D-T192 after the shearing process.

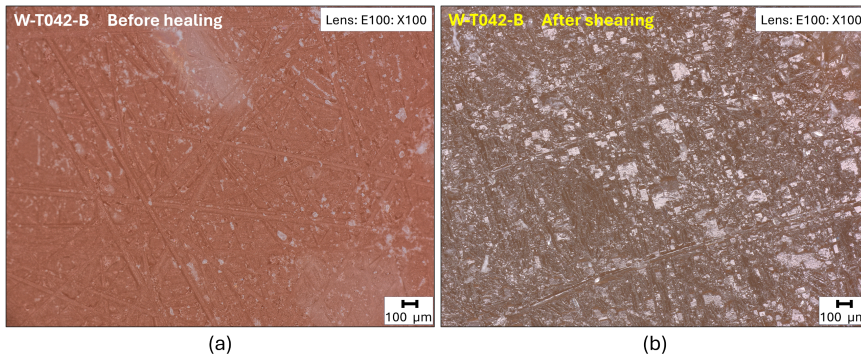


Figure 3.16. shows the microstructure of the fracture surface of sample W-T042-B before healing (a) and after shearing (b) at different locations, captured at 100x magnification.

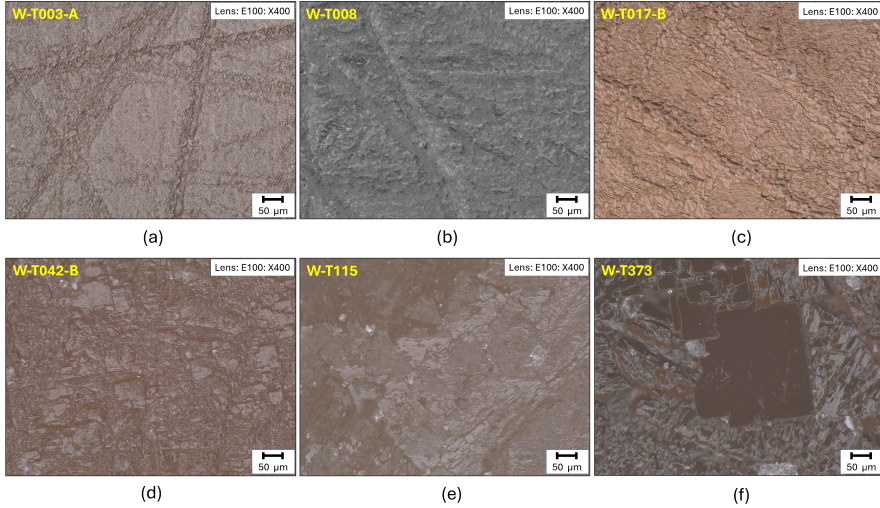


Figure 3.17. (a)-(f) show the crystallization behaviour in sample W-T003-A, W-T008, W-T017-B, W-T042-B, W-T115, W-T373 with 400X magnification.

Comparing the microstructure at the same locations on the fracture surface before static compaction and after shearing for W-T003-A and W-T003-B, it can clearly be seen that initially high areas expand after shearing, and that a small scratch is filled (black dotted circle in Figure 3.18 (a)-(b)). Comparing scratches patterns pre- and post-shear (i.e. Figure 3.18 (c) vs Figure 3.18 (d)), scratches are partially blocked and filled during the healing process. Given that the total weight of this specific sample was unchanged, this suggests other locations may undergo dissolution.

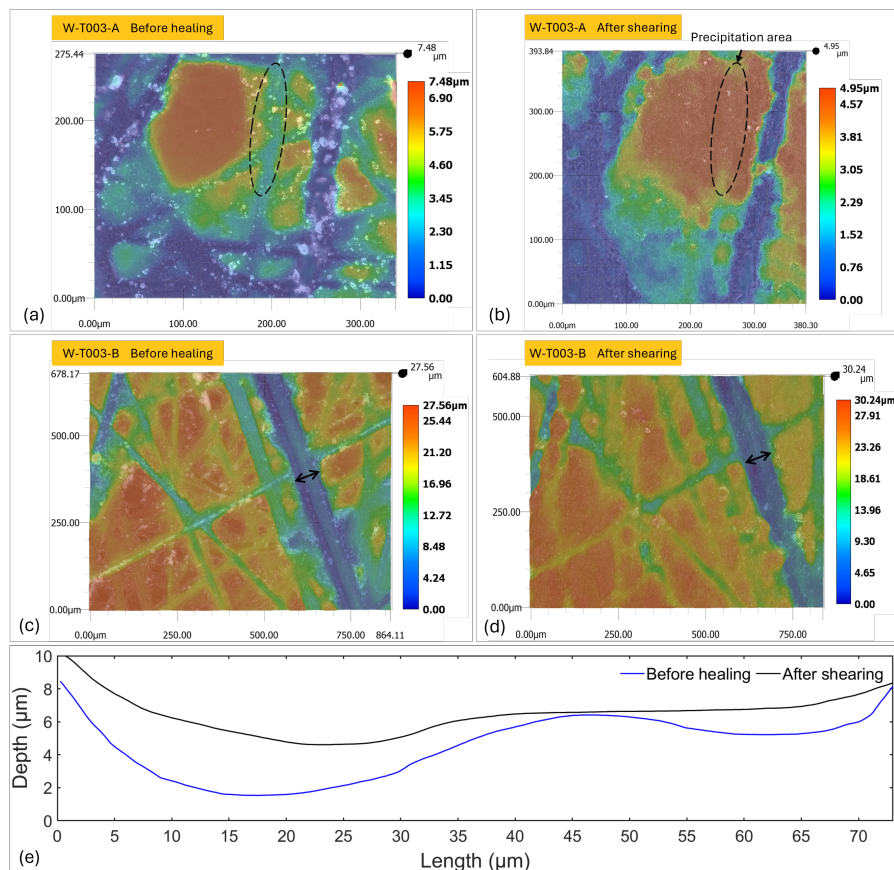


Figure 3.18. (a) and (b) show 3D profiles of the same area on sample W-T003-A at 1000x magnification; (c) and (d) show the same for sample W-T003-B at 400x magnification. (e) presents the cross profile of the scratch before healing and after shearing, corresponding to the double-arrow line in (c) and (d).

3.3.2.3 Micro-CT results

Micro-CT scans are conducted on samples W-T042-B and W-T373 after shearing (Figure 3.19). The W-T042-B sample shows no significant size change compared to its pre-healing dimensions, with the outer boundary length remaining approximately 6 cm after shearing (Figure 3.19 (a)-(b)). The sample's weight is unchanged.

In contrast, the W-T373 sample exhibits notable changes. Relatively large crystals have formed on its outer surface, distributed irregularly and displaying a layered, sheet-like structure. The top outer boundary length decreased from 6 cm to 4.9 cm, indicating dissolution must have occurred in the upper rock salt plate. The bottom boundary length increased to 6.038 cm, exceeding its pre-healing boundary length of 6 cm. The samples were loaded on the top, so the transition from dissolution to precipitation follows the

direction of the compressive load and gravity (Figure 3.19 (c)-(d)). The weight of the W-T373 sample decreases from an average initial weight of 230 g to 196 g after shearing, indicating a material loss of 34 g over 373 days due to dissolution.

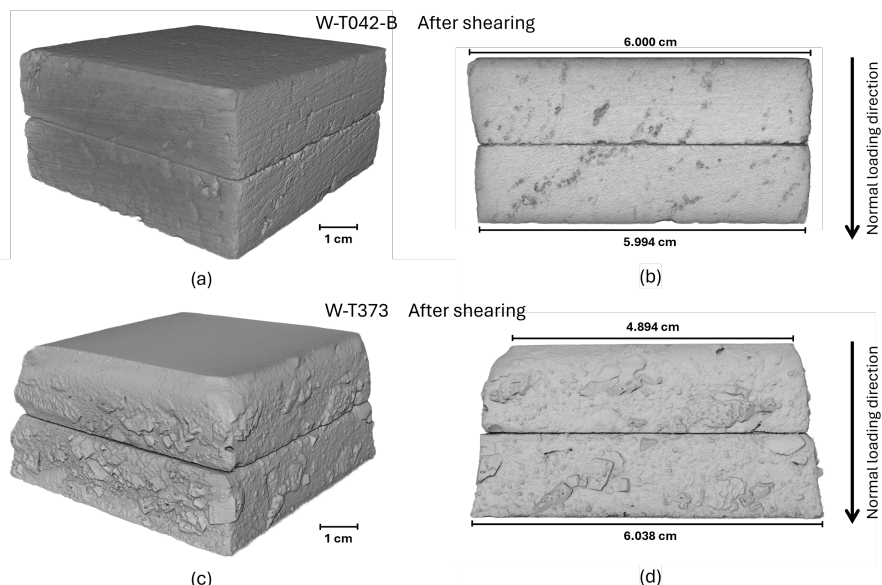


Figure 3.19. (a) and (b) display micro-CT scans of the external view of sample W-T042-B, while (c) and (d) illustrate scans of sample W-T373. Note that the post-shearing samples are incohesive; therefore, they are removed from the shear box individually and repositioned in the CT scanner with zero apparent displacement. This ensures symmetry, which improves scan quality.

3.4 Discussion

3.4.1 Stress response during shearing

Stick-slip behaviour is consistently observed throughout all direct shear experiments, with each event characterised by a gradual stress increase followed by a sudden drop, accompanied by audible acoustic emissions, which is analogous to micro-earthquakes in a laboratory setting. Higher normal loads result in larger stress drops, which qualitatively correlate with the volume of the acoustic emissions (Figure 3.12). This cyclic behaviour is an unstable sliding phenomenon and is first suggested by Brace & Byerlee (1966) as a fundamental mechanism for shallow-focus tectonic earthquakes. Stick-slip behaviour is widely discussed in the field of earthquake mechanics (Ohnaka, 1973.; Mora & Place, 1994; Johnson et al., 2008). Generally, it is considered a frictional process involving the transition from static to kinetic friction (Zhou et al., 2021). This transition enables the release of accumulated elastic energy during the stick phase through frictional sliding in the slip phase, destabilising the fracture and causing a sudden, significant stress drop. This indicates that portions of the fracture surface become

disengaged (Scholz et al., 1972; Gao et al., 1994). Two distinct stick-slip models exist. In the distance-dependent model, asperities require a characteristic time to increase their adhesion strength after contact. Rough macroscopic surfaces adhere through microscopic asperities of a defined length. Therefore, each surface must slip a distance equal to the size of the contacting junctions during shearing. Once this distance is covered, the surfaces enter the slip phase, sliding with a lower kinetic friction force compared to the higher static friction force observed in the stick phase. As the surfaces slip to a new asperity junction, the shear force rises and then decreases after surpassing the junction. The reduction in static friction occurs because, although new asperity junctions form as quickly as old ones break, their adhesion and friction are weaker than those of the previous junctions. As a result, the static stress during the first stick-slip event in each stage is higher than that of subsequent events under the same loading conditions. This behaviour is more pronounced at low normal loads and small horizontal displacements. In contrast, the velocity-dependent model is typically used for wet samples. Under wet conditions, thin liquid films between fracture surfaces generate high static friction when the surfaces are at rest, driven by the solidification of the liquid film. Once the applied shear force exceeds this threshold, the surfaces slide with a lower kinetic friction force as the film transitions into a molten, liquid-like state (i.e., high stress drop). Stick-slip behaviour persists as the liquid film undergoes successive freezing and melting cycles, resulting in distinct periods of sticking and slipping compared to dry samples with the same healing time (Berman et al., 1996).

The behaviour of our dry samples is well described by the distance-dependent model. Here, stress drop and frequency of stick-slip behaviour are influenced by contact surface roughness and normal stress. Under the same loading conditions, smoother surfaces generally exhibit lower friction, higher stick-slip frequencies, and smaller stress drops. Conversely, rougher surfaces, with greater resistance, result in higher stress drops and lower frequencies due to larger stress and elastic energy accumulation before slip occurs. Thus, variations in stress drop and frequency offer insights into fracture surface roughness (Blanke et al., 2021; Zhou et al., 2021). For dry samples, the stress drop increases while the frequency of stick-slip events decreases with longer healing times under each specific normal load (Figure 3.12 (c)-(d)). The long-healing dry sample (D-T192) exhibits greater shear resistance, larger stress drops, and lower stick-slip frequencies during shearing compared to other dry samples. This suggests the possibility that the fracture surface becomes rougher as healing time increases, which is indeed supported by the observation that both the residual friction angle (Figure 3.10 (a)) and the apparent friction coefficient (Figure 3.11 (a)) increase with healing time, as determined using the Mohr-Coulomb criterion (Han et al., 2018; Tang et al., 2021; Ren et al., 2021). Moreover, the RMS roughness measurements from a digital microscope confirm that surface roughness roughly follows an increasing trend with healing time (Figure 3.14).

Wet samples exhibit distinctly different stick-slip behaviour compared to dry samples. For unhealed wet samples (W-T000) prior to healing, once the fracture between the two separated rock salt plates is fully saturated with solution, some effort is required to separate the plates, indicating the presence of cohesion induced by the solution immediately. Additionally, the stress drop in unhealed wet samples is approximately times higher than in unhealed dry samples, while the frequency of stick-slip events is substantially lower in wet samples (Figure 3.12 (b) and (d)). For healed wet samples, the

stress drop and frequency remain consistent regardless of healing time (Figure 3.12 (c)-(d)). This trend is also observed in the residual friction angle (Figure 3.10 (b)) and the apparent friction coefficient (Figure 3.11 (b)). This can be explained by the velocity-dependent model, where the solution within the fracture space acts as the primary factor influencing the shear stress response in wet sample.

3.4.2 Healing mechanisms

Healing behaviour of rock salt fractures is investigated under varying healing conditions and healing time in this study. In dry conditions, the samples exhibit limited but measurable time-dependent recovery for the long healing times (Figure 3.9). Additionally, the healed samples exhibit striations after shearing (Figure 3.15), whereas the non-healed samples lack these noticeable microstructural features. This indicates that some activity must have occurred on the fracture surface during the dry healing process. We interpret the healing behaviour in dry samples as being primarily due to mechanical closure of the fracture, driven plastic deformation (Figure 3.20 (a)). Under normal stress conditions, the deformation of rock salt crystals can relieve stress through dislocation glide, leading to plastic deformation and potentially resulting in creep over extended periods (Sensen et al., 1992; Peach & Spiers, 1996). Moreover, protruding areas on the fracture surface are typically regions of stress concentration. Application of a normal load will increase the local stress in these regions, which should thereby promote significant dislocation movement. As time increases, the dislocation density rises, progressively altering the fracture surface morphology. This process may lead to the interlocking or adhesion of crystal structures on either side of the fracture. When the simulated fracture is sheared post-healing, these changes contribute to the increased shear strength of the rock salt fracture, while also altering the roughness of the fracture surface of dry samples where striations occur on the locations where the top and bottom side of the fracture connected (Ji et al., 2022).

In wet samples, the healing strength recovery is significantly enhanced compared to dry samples, increasing from 44 kPa after 3 days to 243 kPa after 373 days. The average recovery rate declines exponentially over time (Figure 3.9 (c)). Although each data point reflects an independent measurement at a specific healing duration, we interpret these observations collectively as representing a continuous healing process. This assumption is supported by the systematic trend (i.e., log - linear) in the data, which provides a basis for estimating the recovery rate. Furthermore, the log-linear slope in wet samples is approximately seven times steeper than that in dry samples. This indicates that, emphasizing the critical role of the presence of solution facilitates fracture healing in rock salt, as expected based on existing literature. The distinct log-linear relationship with healing time (Figure 3.9 (b)) is consistent with findings from SHS experiments using granular salt (Hunfeld et al., 2020; Niemeijer et al., 2022). It is known that for chemical reaction-dominated healing power-law models may better fit the healing behaviour of reactive materials (Renard et al., 2012; Pluymakers and Niemeijer, 2015). Rapid strength recovery in wet environments can be driven by processes such as pressure solution, surface energy reduction, and recrystallisation, which facilitate material redistribution at the fracture interface and modify surface roughness (Houben et al., 2013; Ji et al., 2022).

Given the log-linear behaviour, we infer one or more of these chemical processes must have occurred.

Fracture closure caused by pressure solution occurs when stress differentials generate a chemical potential gradient under saturated conditions, leading to material dissolve at high-stress concentrations and reprecipitate in lower-stress regions in micrometre scale (Figure 3.20 (b)). We observe an increase in contact area after healing, as indicated by the expansion of red regions in Figure 3.18 (b) (after healing) compared to Figure 3.18 (a) (before healing). These red regions correspond to elevated surfaces that come into contact with the opposing fracture face and are therefore subjected to higher normal stresses. In contrast, the scratches (i.e., valley regions) experience minimal or no normal stress and are partially obstructed and filled by precipitated material in these low-stress areas. A rough calculation shows that approximately $25,716 \mu\text{m}^3$ of rock salt dissolves from high-stress areas (red regions in Figure 3.18 (a)), while about $25,329 \mu\text{m}^3$ rock salt precipitates in low-stress areas (Figure 3.18 (b)). Further evidence is provided by the reduction in valley depth observed in Figure 3.18 (c) and (d), as quantified in Figure 3.18 (e). This decrease in depth indicates salt reprecipitation in low-stress regions, consistent with pressure solution-driven healing. This near mass balance confirms the occurrence of local pressure solution behaviour. Facilitated by solution films and free-face diffusion, this process increases the contact area and effectively “glue” the fracture surfaces, thereby enhancing the mechanical strength of the healed interface. Micro-CT scans reveal that dissolution predominantly occurs in the upper region of the sample's outer surface, while precipitation is observed in the lower region (Figure 3.19). This is likely due to concentration differences caused by the gravity effect, where during the static compaction process the fluid in the upper region transitions from a saturated state to an oversaturated solution at the bottom. However, due to the larger spatial scale involved, this mechanism differs from micro-scale pressure solution, which is driven by local stress at grain contacts.

Recrystallisation can promote fracture closure through grain boundary migration along fluid-filled boundaries, eventually overgrowing the fractures and leaving behind sub-spherical fluid inclusions (Figure 3.20 (c)). After healing and after shearing, crystal boundaries migrate, transforming irregular, high-energy fracture surfaces into (100)-oriented, stepped, and zig-zag morphologies (Figure 3.16 and Figure 3.17), which correspond to the lowest surface energy configuration for NaCl (Bruno et al., 2009). Additionally, crystal size increases over time, with longer healing durations promoting the formation of larger “bridges” between opposing surfaces, thereby enhancing the recovery of mechanical strength. Therefore, in this study our microstructural analysis clearly reveals evidence of recrystallisation, with its effects becoming increasingly pronounced over time.

The last possibility, healing driven by surface energy reduction, would lead to the necking of fractures into tubes and the eventual formation of isolated, sub-spherical fluid inclusions, with material transport occurring via diffusion through thin water films (Figure 3.20 (d)). We have no observations to conclude or exclude this healing mechanism. If it would occur, we would expect that over time, it would lead to disconnection of fracture space, and reduction of the overall interfacial area. This would align with the finding from Ji et al., (2022), which report that rock salt fractures tend to neck down into less well-connected arrays of pores and inclusions at the micrometre scale.

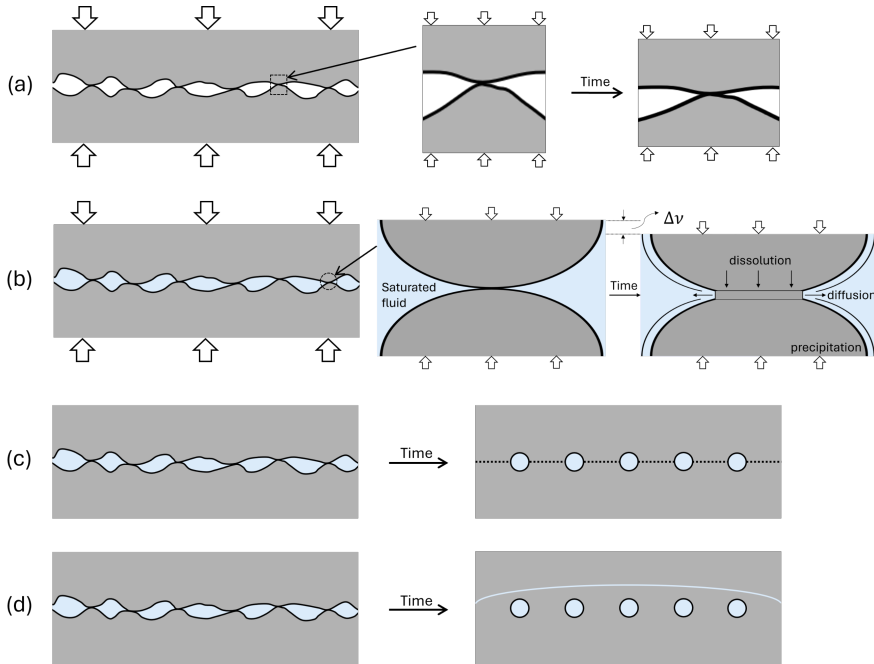


Figure 3.20 (a) mechanical closure caused by plastic deformation in dry condition. In wet rock salt, fracture healing occurs through (b) mechanical closure via pressure solution; (c) closure through recrystallisation process; and (d) narrowing of fractures into isolated tubular or spherical inclusions driven by surface energy and diffusion through water films or brine, adapted from Houben et al., (2013) with modifications.

3.4.3 Implications for energy storage

The excavation of salt caverns typically leads to the formation of a damage zone, which is expected to be saturated with brine (Liu et al., 2023; Kumar et al., 2023). The healing behaviour of rock salt generally follows a log-linear trend over time, with the most rapid strength recovery occurring within the first month. Even under dry conditions, the shear strength of fractured rock salt approximately doubles within six months. Our experiments show that strength recovery is significantly more pronounced in the presence of saturated brine. In wet conditions, fractures in the damage zone can regain up to six times their shear strength of initial fracture within one year, substantially enhancing the structural integrity of the rock mass, even when only minor damage is present.

This trend has important implications for optimising the timing of brine injection and energy extraction in subsurface energy storage systems (Liu et al., 2018). Salt caverns used for gas storage typically follow two main operational cycles each year, with gas injected during low demand seasons and withdrawn during high demand periods. These cycles are often accompanied by shorter term adjustments to balance fluctuations in supply and demand. When the interval between cycling phases exceeds one month, fractures in the damage zone have sufficient time to undergo meaningful healing, enhancing the safety and long-term stability of salt cavern. Moreover, the observed

increase in fracture surface roughness over time, driven by pressure solution, recrystallization, and surface energy reduction processes, enhances interlocking between fracture faces. This interlocking further contributes to strength recovery and improves resistance to slip and fracture propagation. As a result, mechanical interlocking may reduce leakage risks and extend the operational lifespan of storage caverns, even under cyclic loading conditions.

3.5 Conclusions

In this study, we performed a series of two-step experiments, with static dry and wet healing of rock salt, followed by direct shear test to investigate the evolution of shear strength of rock salt fractures with healing time. Additionally, we analysed the evolution of fracture surface topography using a digital microscope and micro-CT, both before static compaction and after shearing, to evaluate changes in surface morphology. Our main conclusions are as follows:

- (1) Dry and wet healing show a log-linear relationship with time, with the recovery rate in wet samples being seven times greater than that in dry samples in terms of the log-linear slope.
- (2) Healing in dry samples can be attributed to plastic flow, as observed in microstructural features such as slip-parallel striations in fracture surface. Additionally, dynamic behaviour is characterised by an increase in both the residual friction angle and apparent friction coefficient over time.
- (3) Healing in wet samples can be attributed to pressure solution, recrystallisation, and possibly surface energy minimisation processes, as evidenced by dissolution and precipitation, as well as the formation and growth of salt crystals on the fracture surface.
- (4) A significant difference in stick-slip behaviour is observed between dry and wet samples. This disparity may be due to the applicability of a distance-dependent model of stick-slip behaviour in dry conditions and a velocity-dependent model in wet conditions.

3.6 References

- Berman, A. D., Ducker, W. A., & Israelachvili, J. N., 1996. Origin and Characterization of Different Stick-Slip Friction Mechanisms. *Langmuir*, 12(19), 4559–4563.
- Blanco-Martín, L., Azabou, M., Rouabhi, A., Hadj-Hassen, F. and Hévin, G., 2022. Insights from an experimental campaign on rock salt and implications at the cavern scale. In *The Mechanical Behavior of Salt X* (pp. 119–129). CRC Press.
- Blanke, A., Kwiatak, G., Goebel, T. H. W., Bohnhoff, M., & Dresen, G., 2021. Stress drop-magnitude dependence of acoustic emissions during laboratory stick-slip. *Geophysical Journal International*, 224(2), 1371–1380. <https://doi.org/10.1093/gji/ggaa524>
- Bos, B., Peach, C. J., & Spiers, C. J., 2000. Slip behavior of simulated gouge-bearing faults under conditions favoring pressure solution. *Journal of Geophysical Research: Solid Earth*, 105(B7), 16699–16717. <https://doi.org/10.1029/2000jb900089>
- Brace, W. F., & Byerlee, J. D., 1966. Stick-slip as a mechanism for earthquakes. *Science*, 153(3739), 990–992. <https://doi.org/10.1126/science.153.3739.990>
- Brodsky, N. S., & Munson, D. E., 1994. Thermomechanical damage recovery parameters for rocksalt from the Waste Isolation Pilot Plant. In *Proceedings of the ARMA North America Rock Mechanics Symposium (ARMA-1994)*.
- Brodsky, N. S., 1990. Crack closure and healing studies in WIPP salt using compressional-wave velocity and attenuation measurements: Test methods and results. Sandia National Laboratories Report.
- Bruno, M., Aquilano, D., & Prencepio, M., 2009. Quantum-mechanical and thermodynamical study on the (110) and reconstructed (111) faces of NaCl crystals. *Crystal Growth & Design*, 9(4), 1912–1916. <https://doi.org/10.1021/cg801144x>
- Chan, K. S., Brodsky, N. S., Fossum, A. F., Bodner, S. R., & Munson, D. E., 1994. Damage-induced non-associated inelastic flow in rock salt. *International Journal of Plasticity*, 10(6), 623–642. [https://doi.org/10.1016/0749-6419\(94\)90026-4](https://doi.org/10.1016/0749-6419(94)90026-4)
- Chen, J., Ren, S., Yang, C., Jiang, D., & Li, L., 2013. Self-healing characteristics of damaged rock salt under different healing conditions. *Materials*, 6(8), 3438–3450. <https://doi.org/10.3390/ma6083438>
- Costin, L. S., & Wawersik, W. R., 1980. Creep healing of fractures in rock salt. Sandia National Laboratories Report (SAND-80-0392).
- Dieterich, J. H., & Kilgore, B. D., 1994. Direct observation of frictional contacts: New insights for state-dependent properties. *Pure and Applied Geophysics*, 143, 283–302.
- Dieterich, J. H., 1972. Time-dependent friction in rocks. *Journal of Geophysical Research*, 77(20), 3690–3697. <https://doi.org/10.1029/jb077i020p03690>
- Fuenkajorn, K., & Phueakphum, D., 2011. Laboratory assessment of healing of fractures in rock salt. *Bulletin of Engineering Geology and the Environment*, 70(4), 665–672. <https://doi.org/10.1007/s10064-011-0370-y>
- Gao, C., Kuhlmann-Wilsdorf, D., & Makel, D. D., 1994. The dynamic analysis of stick-slip motion. *Wear*, 173(1–2), 1–12. [https://doi.org/10.1016/0043-1648\(94\)90251-8](https://doi.org/10.1016/0043-1648(94)90251-8)
- Han, F., Ganju, E., Salgado, R., & Prezzi, M., 2018. Effects of interface roughness, particle geometry, and gradation on the sand–steel interface friction angle. *Journal of Geotechnical and Geoenvironmental Engineering*, 144(12), 04018096. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001990](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001990)
- Houben, M. E., ten Hove, A., Peach, C. J., & Spiers, C. J., 2013. Crack healing in rocksalt via diffusion in adsorbed aqueous films: Microphysical modelling versus experiments. *Physics and Chemistry of the Earth*, 64, 95–104. <https://doi.org/10.1016/j.pce.2012.10.001>
- Hunfeld, L. B., Chen, J., Hol, S., Niemeijer, A. R., & Spiers, C. J., 2020. Healing behavior of simulated fault gouges from the Groningen gas field and implications for induced fault reactivation. *Journal of Geophysical Research: Solid Earth*, 125(7). <https://doi.org/10.1029/2019JB018790>
- Hunsche, U., & Hampel, A., 1999. Rock salt—the mechanical properties of the host-rock material for a radioactive-waste repository. *Engineering Geology*, 52(3–4), 271–291. [https://doi.org/10.1016/S0013-7952\(99\)00011-3](https://doi.org/10.1016/S0013-7952(99)00011-3)
- Istvan, J. A., Evans, L. J., Weber, J. H., & Devine, C., 1997. Rock mechanics for gas storage in bedded salt caverns. *International Journal of Rock Mechanics and Mining Sciences*, 34(3–4), 142.e1. [https://doi.org/10.1016/S1365-1609\(97\)00108-1](https://doi.org/10.1016/S1365-1609(97)00108-1)
- Ji, Y., Spiers, C. J., Hangx, S. J. T., de Bresser, J. H. P., & Drury, M. R., 2022. 4D microtomography of brine-assisted healing processes in deformation-damaged rocksalt: A first look. In *The Mechanical Behavior of Salt X* (pp. 88–97).
- Johnson, P. A., Savage, H., Knuth, M., Gombert, J., & Marone, C., 2008. Effects of acoustic waves on stick-slip in granular media and implications for earthquakes. *Nature*, 451(7174), 57–60. <https://doi.org/10.1038/nature06440>
- Kanagawa, K., Cox, S. F., & Zhang, S., 2000. Effects of dissolution-precipitation processes on the strength and mechanical behavior of quartz gouge at high-temperature hydrothermal conditions. *Journal of Geophysical Research: Solid Earth*, 105(B5), 11115–11126. <https://doi.org/10.1029/2000jb900038>
- Karner, S. L., Marone, C., & Evans, B., 1997. Laboratory study of fault healing and lithification in simulated fault gouge under hydrothermal conditions. *Tectonophysics*, 277(1–3), 41–55. [https://doi.org/10.1016/S0040-1951\(97\)00077-2](https://doi.org/10.1016/S0040-1951(97)00077-2)
- King, M., Jain, A., Bhakar, R., Mathur, J., & Wang, J., 2021. Overview of current compressed-air energy-storage projects and analysis of the potential underground storage capacity in India and the UK. *Renewable and Sustainable Energy Reviews*, 139, 110705. <https://doi.org/10.1016/j.rser.2021.110705>
- Kumar, K.R., Honorio, H., Chandra, D., Lesueur, M. and Hajibeygi, H., 2023. Comprehensive review of geomechanics of underground hydrogen storage in depleted reservoirs and salt caverns. *Journal of energy storage*, 73, p.108912. <https://doi.org/10.1016/j.est.2023.108912>
- Li, Z., Kang, Y., Fan, J., Fourmeau, M., Chen, J., Jiang, D., & Nelias, D., 2024. Macroscopic experimental study and microscopic phenomenon analysis of damage self-healing in salt rock. *Engineering Geology*, 338, 107634. <https://doi.org/10.1016/j.enggeo.2024.107634>
- Liu, W., Jiang, D., Chen, J., Daemen, J. J. K., Tang, K., & Wu, F., 2018. Comprehensive feasibility study of two-well horizontal caverns for natural-gas storage in thinly-bedded salt rocks in China. *Energy*, 143, 1006–1019. <https://doi.org/10.1016/j.energy.2017.10.126>
- Liu, W., Li, Q., Yang, C., Shi, X., Wan, J., Jurado, M. J., & He, Y., 2023. The role of underground salt caverns for large-scale energy storage: A review and prospects. *Energy Storage Materials*, 63, 103045. <https://doi.org/10.1016/j.ensm.2023.103045>
- Mirzaghobranali, A., Nemcik, J., & Aziz, N., 2014. Effects of shear rate on cyclic-loading shear behaviour of rock joints under constant normal stiffness conditions. *Rock Mechanics and Rock Engineering*, 47(5), 1931–1938. <https://doi.org/10.1007/s00603-013-0453-0>
- Mora, P., & Place, D., 1994. Simulation of the frictional stick-slip instability. *Pure and Applied Geophysics*, 143, 61–87.

- Nakatani, M., & Scholz, C. H., 2004. Frictional healing of quartz gouge under hydrothermal conditions: 1. Experimental evidence for solution transfer healing mechanism. *Journal of Geophysical Research: Solid Earth*, 109(B7). <https://doi.org/10.1029/2001JB001522>
- Niemeijer, A., Marone, C., & Elsworth, D., 2008. Healing of simulated fault gouges aided by pressure solution: Results from rock-analogue experiments. *Journal of Geophysical Research: Solid Earth*, 113(4). <https://doi.org/10.1029/2007JB005376>
- Niemeijer, A., van den Ende, M., Marone, C., Elsworth, D., & Spiers, C., 2022. A review of frictional sliding on brine-penetrated faults in salt. In *The Mechanical Behavior of Salt X* (pp. 38–45).
- Ohnaka, M., 1973. Experimental studies of stick-slip and their application to the earthquake source mechanism. *Journal of Physics of the Earth*, 21(3), 285–303.
- Olsen, M. P., Scholz, C. H., & Léger, A., 1998. Healing and sealing of a simulated fault gouge under hydrothermal conditions: Implications for fault healing. *Journal of Geophysical Research: Solid Earth*, 103(B4), 7421–7430. <https://doi.org/10.1029/97JB03402>
- Peach, C. J., & Spiers, C. J., 1996. Influence of crystal-plastic deformation on dilatancy and permeability development in synthetic salt rock. *Tectonophysics*, 256(1–4), 101–128. [https://doi.org/10.1016/0040-1951\(95\)00170-0](https://doi.org/10.1016/0040-1951(95)00170-0)
- Peach, C. J., 1991. Influence of deformation on the fluid-transport properties of salt rocks.
- Pfeifle, T. W., & Hurtado, L. D., 1998. Permeability of natural rock salt from the Waste Isolation Pilot Plant (WIPP) during damage evolution and healing. *International Journal of Rock Mechanics and Mining Sciences*, 35(4–5), 637–638. [https://doi.org/10.1016/S0148-9062\(98\)00044-8](https://doi.org/10.1016/S0148-9062(98)00044-8)
- Pluymakers, A. M. H., & Niemeijer, A. R., 2015. Healing and sliding stability of simulated anhydrite fault gouge: Effects of water, temperature and CO₂. *Tectonophysics*, 656, 111–130. <https://doi.org/10.1016/j.tecto.2015.06.012>
- Ravelli, E. and Martinez, R.G., 2022. Environmental risk factors of airborne viral transmission: Humidity, Influenza and SARS-CoV-2 in the Netherlands. *Spatial and Spatio-temporal Epidemiology*, 41, p.100432. <https://doi.org/10.1016/j.sste.2021.100432>
- Ren, S., Zhang, Y., Xu, N., Wu, R., Liu, X., & Du, G., 2021. Mobilized strength of gravelly sliding-zone soil in a reactivated landslide: A case study of a giant landslide on the north-eastern margin of the Tibet Plateau. *Environmental Earth Sciences*, 80(12), 434. <https://doi.org/10.1007/s12665-021-09638-y>
- Renard, F., Beauprêtre, S., Voisin, C., Zigone, D., Candela, T., Dysthe, D. K., & Gratier, J. P., 2012. Strength evolution of a reactive frictional interface is controlled by the dynamics of contacts and chemical effects. *Earth and Planetary Science Letters*, 341–344, 20–34. <https://doi.org/10.1016/j.epsl.2012.04.048>
- Renard, F., Gratier, J. P., & Jamveit, B., 2000. Kinetics of crack-sealing, intergranular pressure solution, and compaction around active faults. *Journal of Structural Geology*, 22(10), 1395–1407. [https://doi.org/10.1016/S0191-8141\(00\)00064-X](https://doi.org/10.1016/S0191-8141(00)00064-X)
- Salzer, K., Popp, T., & Böhnel, H., 2017. Mechanical and permeability properties of highly pre-compacted granular-salt bricks. In *The Mechanical Behavior of Salt – Understanding of THMC Processes in Salt* (pp. 239–248).
- Scholz, C., Molnar, P., & Johnson, T., 1972. Detailed studies of frictional sliding of granite and implications for the earthquake mechanism. *Journal of Geophysical Research*, 77(32), 6392–6406. <https://doi.org/10.1029/jb077i032p06392>
- Senseney, P. E., Hansen, F. D., Russell, J. E., Carter, N. L., & Handin, J. W., 1992. Mechanical behaviour of rock salt: Phenomenology and micromechanisms. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 29(4), 363–378. [https://doi.org/10.1016/0148-9062\(92\)90513-Y](https://doi.org/10.1016/0148-9062(92)90513-Y)
- Stormont, J. C., & Daemen, J. J. K., 1992. Laboratory study of gas permeability changes in rock salt during deformation. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 29(4), 325–342. [https://doi.org/10.1016/0148-9062\(92\)90510-7](https://doi.org/10.1016/0148-9062(92)90510-7)
- Sutherland, H. J., & Cave, S. P., 1980. Argon-gas permeability of New Mexico rock salt under hydrostatic compression. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 17(5), 281–288. [https://doi.org/10.1016/0148-9062\(80\)90810-4](https://doi.org/10.1016/0148-9062(80)90810-4)
- Tang, W., & Lin, H., 2021. Influence of internal friction angle and interface roughness on shear behavior of mortar-rock binary-medium joints. *Geotechnical and Geological Engineering*, 39, 3917–3929. <https://doi.org/10.1007/s10706-021-01736-9>
- Tang, Z. C., & Wong, L. N. Y., 2016. Influences of normal loading rate and shear velocity on the shear behavior of artificial rock joints. *Rock Mechanics and Rock Engineering*, 49(6), 2165–2172. <https://doi.org/10.1007/s00603-015-0822-y>
- Tenthorey, E., Cox, S. F., & Todd, H. F., 2003. Evolution of strength recovery and permeability during fluid-rock reaction in experimental fault zones. *Earth and Planetary Science Letters*, 206(1–2), 161–172. [https://doi.org/10.1016/S0012-821X\(02\)01082-8](https://doi.org/10.1016/S0012-821X(02)01082-8)
- Tsang, C. F., Bernier, F., & Davies, C., 2005. Geohydromechanical processes in the Excavation Damaged Zone in crystalline rock, rock salt, and indurated and plastic clays—in the context of radioactive-waste disposal. *International Journal of Rock Mechanics and Mining Sciences*, 42(1), 109–125. <https://doi.org/10.1016/j.ijrmms.2004.08.003>
- Urai, J. L., Spiers, C. J., Zwart, H. J., & Lister, G. S., 1986. Weakening of rock salt by water during long-term creep. *Nature*, 324(6097), 554–557. <https://doi.org/10.1038/324554a0>
- Williams, J. D. O., Williamson, J. P., Parkes, D., Evans, D. J., Kirk, K. L., Sunny, N., Hough, E., Vosper, H., & Akhurst, M. C., 2022. Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt-cavern storage potential of bedded halite formations. *Journal of Energy Storage*, 53, 105109. <https://doi.org/10.1016/j.est.2022.105109>
- Yasuhashi, H., 2004. Evolution of permeability in a natural fracture: Significant role of pressure solution. *Journal of Geophysical Research*, 109(B3). <https://doi.org/10.1029/2003jb002663>
- Zhou, X., He, Y., & Shou, Y., 2021. Experimental investigation of the effects of loading rate, contact roughness, and normal stress on the stick-slip behavior of faults. *Tectonophysics*, 816, 229027. <https://doi.org/10.1016/j.tecto.2021.229027>

4. Healing behaviour of rock salt fractures with varying surface roughness

Abstract: *Rock salt healing enhances the integrity of underground storage systems, but the effect of fracture surface roughness remains unclear. In this study, we investigate the shear strength recovery of artificial fractures in natural rock salt under varying initial roughness and healing conditions in a 2-step process. First, samples of different initial roughness (polished with 40 or 80 grit sandpaper) are compacted and allowed to heal up to 17 days, either under dry conditions or in the presence of saturated solution, under 54.4 kPa normal stress. Second, peak strength and sliding behaviour are determined with a standard shear box test, with incremental normal loads. The fracture surface geometry is analysed before healing and after shearing using digital microscopy. Results show that under dry conditions limited strength recovery occurs only for smooth fractures. In wet conditions, smooth fractures heal significantly, while rough fractures exhibit only marginal improvement. Healing in dry samples is attributed to dislocation activity, demonstrated by visible post-shear striations. The enhanced healing observed in smooth wet samples compared to their rough counterparts is attributed to recrystallization, which facilitates the formation of "bridges". Our results highlight a clear inhibitory effect of surface roughness on strength recovery, even for fully wet surfaces.*

4.1 Introduction

Rock salt is a highly valued seal for energy storage and geological nuclear waste disposal due to its low permeability, low porosity, ductility, and water-soluble extraction properties (Desbois et al., 2012; Kishida et al., 2012). However, when constructing such facilities, rock salt (or any other seal) is subject to combined thermal, chemical, and mechanical stresses changes, which may lead to fracture initiation and propagation, creating mechanical weaknesses or preferential pathways that in turn may compromise sealing efficiency (Houben et al., 2013). The healing behaviour of rock salt involves restoring mechanical properties, reversing damage effects, and is typically associated with a reduction in permeability (i.e., sealing behaviour) (Sutherland & Cave, 1980; Peach, 1991; Fuenkajorn & Phueakphum, 2011). This capacity of rock salt for natural strength recovery will aid in maintaining the structural integrity of storage systems over prolonged periods. Therefore, understanding of the healing behaviour of rock salt is crucial for ensuring the safety and reliability of such underground storage systems.

In recent decades, studies have quantitatively evaluated the healing process by examining changes in tensile and shear strengths (Salzer et al. 2007; Li et al., 2024), friction coefficient and cohesion (Bos et al., 2000; Kishida et al., 2012; van den Ende & Niemeijer, 2019), under different conditions of confining pressure, healing time, and initial damage degree (Fuenkajorn & Phueakphum, 2011; Zhang et al., 2024). Studies on the effect of healing time on frictional strength recovery in quartz gouges indicate that longer hold periods lead to a higher static coefficient of friction and increased shear strength during subsequent loading (Karner et al., 1997; Kanagawa et al., 2000). The friction increase generally follows a linear-logarithmic relationship with holding time, in accordance with Dieterich's law (Dieterich, 1972; Dieterich, 1994). However, for reactive materials, a power-law relationship may offer a more accurate fit (Renard et al., 2012; Pluymakers and Niemeijer, 2015). In simulated salt gouges, the presence of saturated solution significantly accelerates the healing process (Bos & Spiers, 2002). Niemeijer et al. (2008) found that healing rates of salt gouges in saturated brine at 65°C are an order of magnitude higher than those of dry salt and water-saturated quartz. These studies primarily focus on investigating strength recovery in faults between earthquake events (Karner et al., 1997; Kanagawa et al., 2000; Niemeijer et al. 2008; Renard et al., 2012; Pluymakers and Niemeijer, 2015). Salzer et al. (2007) conducted shear tests on dry and wet salt-brick surfaces and used the Mohr-Coulomb criterion to characterize the mechanical properties of the discontinuity plane. Their results showed brine strengthened cohesion and friction, consistent with findings by Li et al. (2024), who observed accelerated healing in wet rock salt samples and no healing in dry samples in Brazilian splitting tests.

Fracture surface roughness also plays a critical role in rock salt healing. Fuenkajorn & Phueakphum (2011) investigated the impact of tension-induced, saw-cut, and smooth-polished fractures on the healing of rock salt. They found that fractures formed by the separation or splitting of salt crystals heal easily under low stress within a short period. However, a quantitative relationship between fracture surface roughness and healing behaviour for salt specifically has not been established. Microscale observation studies have investigated the mechanisms behind permeability reduction and fracture geometry evolution, which both occur during healing of rock salt (Renard et al., 2004; Ji et al., 2022).

Ji et al. (2022) used microtomography to show that brine-assisted self-healing in damaged salt transformed fractures to become faceted and discontinuous, increasing tortuosity and reducing fracture network connectivity. Li et al. (2024) used SEM to document crystal growth along fractures. The crystals expanded until they contacted the opposite side, resulting in segmentation of the fracture along its length. Previous studies have primarily focused on either mechanical recovery following healing, or the evolution of fracture surface geometry, or the morphology of rock salt granules during healing, leaving gaps in understanding how initial fracture surface roughness affects the healing efficiency of rock salt fractures.

In this study, we investigate shear strength recovery in rock salt fractures through a two-step process, where artificial fractures with varying surface roughness first undergo static healing under either dry conditions or in a saturated solution, after which the healed samples are used in direct shear box tests. We examine the fracture surface geometry before healing and after shearing with a digital microscope. The results are analyzed in terms of mechanical recovery and microstructural changes of rock salt fractures, focusing on the effects of surface roughness, healing time and saturated brine on healing behaviour.

4.2 Methodology

4.2.1 Sample preparation

Original samples are first hand-cut with a saw to fit the shear box size. The fracture surfaces are then manually polished with 40-grit (rough) or 80-grit (smooth) sandpaper to create two levels of surface roughness. The healing samples consist thus each of a set of two rock salt plates with identical surface roughness levels, each measuring 60 ± 0.5 mm in length, 60 ± 0.5 mm in width, and 14 ± 0.2 mm in depth (see Figure 4.1 (a)). Before the two plates undergo healing, the microstructure of the rock salt surfaces is observed using a digital microscope (Keyence VHX-7000), and the surface roughness is quantified using

the root mean square roughness ($R_q = \sqrt{\frac{1}{N} \sum_{i=1}^N Z_i^2}$, where Z_i is the height of each point relative to the mean surface, and N is the total number of measured points) with the Keyence analysis software, based on the average of 2-3 line measurements taken parallel to the planned shear direction, as in chapter 3. The roughness of smooth fracture surfaces before healing and shearing, such as SW-T03 ($3.52 \mu\text{m}$) and SW-T17 ($3.40 \mu\text{m}$), is about 2 - 4 times smaller than the pre-experimental rough surfaces, which measure $7.28 \mu\text{m}$ in RW-T03 and $10.85 \mu\text{m}$ in RW-T17.

To heal the samples under dry conditions, the two plates are placed inside double ziplock bag (closed), with the inner bag containing five sachets of silica gel desiccant. This prevents the rock salt fracture surfaces from drawing in extra moisture from the air, thereby maintaining the fracture in a steady state of low-humidity ("dry") conditions compared to the air humidity. To heal the sample under wet conditions, samples are fully immersed in saturated brine contained within a double ziplock bag configuration. The brine is prepared using crushed material from the original rock salt block. Then the samples are subjected to static compaction under a 20 kg load (equivalent to 55.5 kPa) applied by placing weights on top on the outside of the ziplock bags for healing times of

3 or 17 days under either dry or wet conditions (Figure 4.1 (b)-(c)). A summary of all experiments is provided in Table 4.1.

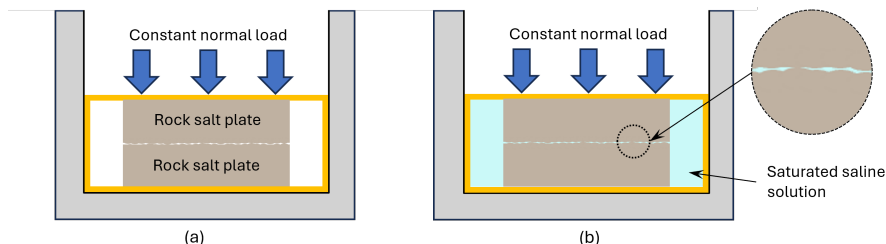


Figure 4.1. (a) A set of rock salt plates prepared for pre-healing, intended for use in shear box tests. The visible band is sellotape, which will be removed before shearing. (b)–(c) Schematics illustrating the sample healing process under dry and wet conditions, respectively. The yellow line represents a plastic bag that isolates the compaction system from the external environment, effectively preventing air infiltration and/or solution evaporation.

4.2.2 Direct shear box experiments

Following static healing, samples are carefully placed into the direct shear apparatus (ELE INTERNATIONAL). All tests are conducted at room temperature and ambient humidity. For both dry and wet conditions, non-healed samples (zero days of healing) are compared. Dry samples with zero days of healing are placed into the shear box without additional preparation, while wet samples with zero days of healing are immersed in a brine bath for a few minutes before shearing. For all wet samples, the fracture surfaces are still wet during the shear experiment, since they are transferred directly from saturated brine, with shearing initiated within minutes after removal from the static loading configuration. The shear velocity is constant and set to 0.5 mm/min. A load-stepping procedure is used, with normal loads of 196 N (20 kg), 392 N (40 kg), 784 N (80 kg), 1568 N (160 kg), and 3136 N (320 kg). These five loads are applied in pre-programmed horizontal displacement intervals of 0 – 3 mm, 3 – 4.5 mm, 4.5 – 6 mm, 6 – 7.5 mm, and 7.5–9 mm, respectively, designated as P1, P2, P3, P4, and P5 (illustrated by the green curve in Figure 4.2). Zero displacement is defined as the point when the direct shear box begins operation, even though not all samples establish immediate contact.

4.2.3 Data processing

Real-time normal stress and shear stress on the contact surface are calculated by dividing the normal load and measured shear force by the load-bearing fracture surface area. Figure 4.2 presents SD-T00 to illustrate the progression of an experiment. The first peak shear stress observed during the P1 stage is defined as the healing strength (τ_H), which evaluates the healing extent of salt rock fractures; a higher healing strength indicates a stronger fracture healing effect. Furthermore, many experiments exhibit stick-slip behaviour, i.e., the steep rises and drops in shear stress response observed in stage P1-P2-P3-P4-P5 in SD-T00, despite the stick-slip event being subtle in P1 (blue curve in

Figure 4.2). In such cases, the average shear stress for each stage is calculated from the peak and valley shear stresses within that stage. Subsequently, average shear and corresponding normal stresses are determined by averaging across consecutive incremental loadings (i.e., the average between the blue and yellow dots in P5). The shear - normal stress relationship is then evaluated to determine the coefficient of residual friction based on Mohr-Coulomb criterion: maximum shear stresses with their corresponding normal stresses are used to determine the high residual friction angle, while minimum shear stresses are used to calculate the low residual friction angle. The evolution of cohesion is excluded from the analysis, as the primary focus is on dynamic sliding behaviour.

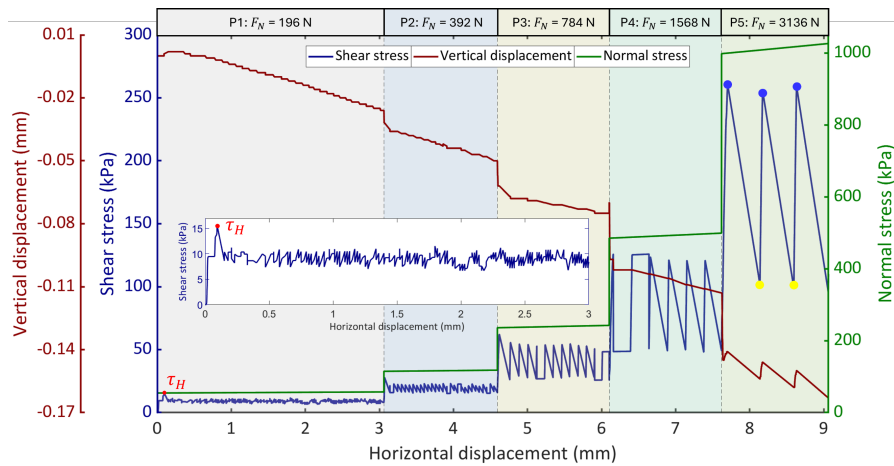


Figure 4.2. Example curves from SD-T00. The blue, red, and green curves represent shear stress, vertical displacement, and normal stress versus horizontal displacement.

Table 4.1. List of experiments and results presented in this study. The test samples are labelled as follows: "D" or "W" indicates dry or wet healing conditions, "TXXX" specifies the healing time in days, and "A" or "B" denotes replicate samples. Smooth fracture surface samples presented in Chapter 3 include SD-T00, SD-T17, SW-T00, SW-T03, and SW-T17, corresponding to experimental samples D-T000, D-T017, W-T000, W-T003-A, and W-T017-A.

Exp.	Healing condition	Healing time (Days)	Healing strength (kPa)	Residual friction angle (°)
Smooth fracture surface, polished with 80-grit				
SD-T00	Dry	0	15.5	5.4 -16.1
SD-T17	Dry	17	18.2	6.5 - 14.5
SW-T00	Wet	0	50.9	0 - 41.5
SW-T03	Wet	3	95.1	0 - 40.3
SW-T17	Wet	17	108.0	0 - 40.5
Rough fracture surface, polished with 40-grit				
RD-T00	Dry	0	35.7	3.3 - 33.8
RD-T17	Dry	17	35.7	14.0 - 25.5
RW-T00	Wet	0	51.1	0 - 43.4
RW-T03	Wet	3	55.7	0 - 43.5
RW-T17	Wet	17	58.4	0-40.8

4.3 Results

All samples display an initial shear stress peak during the P1 stage (Figure 4.3). Prior to the peak strength τ_H , dry samples exhibit a relatively steep stress buildup (P1 stage in Figure 4.3 (a)-(b)), whereas wet samples demonstrate a more gradual increase (P1 stage in Figure 4.3 (c)-(e)). Following the initial shear stress peak, which represents healing strength, RW-T03 exhibited stable sliding during P1 before transitioning to stick-slip behaviour. All other samples exhibit stick-slip behaviour throughout, with each event producing an audible acoustic emission. Higher normal load leads to larger amplitude, and amplitude correlates qualitatively with the volume of the acoustic emission. In dry, unhealed samples, the rough sample (RD-T00) exhibits stick-slip amplitudes 2–10 times larger than those of the smooth sample (SD-T00), with the difference decreasing progressively from 10 times at P2 to 2 times at P5 (Figure 4.3 (a)). After 17 days of healing under dry conditions, the rough sample RD-T17 shows stick-slip amplitudes approximately 1.5 times larger than those of the smooth sample SD-T17 (Figure 4.3 (b)). In wet, unhealed samples and samples healed for 3 days, the stick-slip amplitudes at P2–P5 remain unchanged (Figure 4.3 (c) and (d)). For the wet sample healed for 17 days, the rough sample (RW-T17) exhibits stick-slip amplitudes 1.2 times larger than those of the smooth sample (SW-T17) (Figure 4.3 (e)). The amplitudes of stick-slip events in wet samples are consistently larger than those in dry samples, irrespective of surface roughness and healing time.

4.3.1 Healing strength

Fracture surface roughness, brine presence, and healing time all impact healing strength (Figure 4.4 (d)). In dry unhealed samples, RD-T00 with a rough fracture surface demonstrates higher healing strength (36 kPa) compared to SD-T00 (15 kPa). After 17 days of dry healing, the healing strength of smooth sample SD-T17 slightly increases to 18 kPa, while RD-T17 retains strength of 36 kPa, i.e., identical to that of the unhealed sample RD-T00.

The wet unhealed samples, SW-T00 and RW-T00, exhibit identical healing strengths of 51 kPa. After 3 days of healing, the smooth wet sample (SW-T03) shows a significant increase in healing strength to 95 kPa, while the rough wet sample (RW-T03) experiences only a slight increase to 55 kPa. After 17 days of healing, the healing strength further increases to 108 kPa for SW-T17 and 58 kPa for RW-T17. These results indicate that for smooth wet samples, healing strength increases significantly over time, from 51 kPa (SW-T00) to 95 kPa (SW-T03) and then to 108 kPa (SW-T17), where the rate of increase diminishes with time. In contrast, rough wet samples show only a marginal increase in healing strength, rising from 51 kPa (RW-T00) to 56 kPa (RW-T03) and finally to 58 kPa (RW-T17). There is a clear log-linear relationship with healing time, with smooth samples exhibiting a log-linear slope of 24 kPa/lg(day) and rough samples a slope of 3.2 kPa/lg(day) (Figure 4.4 (a)).

Comparing dry and wet samples, the wet, unhealed samples with smooth surface (SW-T00, 51 kPa) exhibit the healing strength three times higher than their dry counterparts (SD-T00, 15 kPa). For rough fracture surfaces, the healing strength improves by

approximately 1.5 times, increasing from 36 kPa in dry samples (RD-T00) to 51 kPa in wet samples (RW-T00).

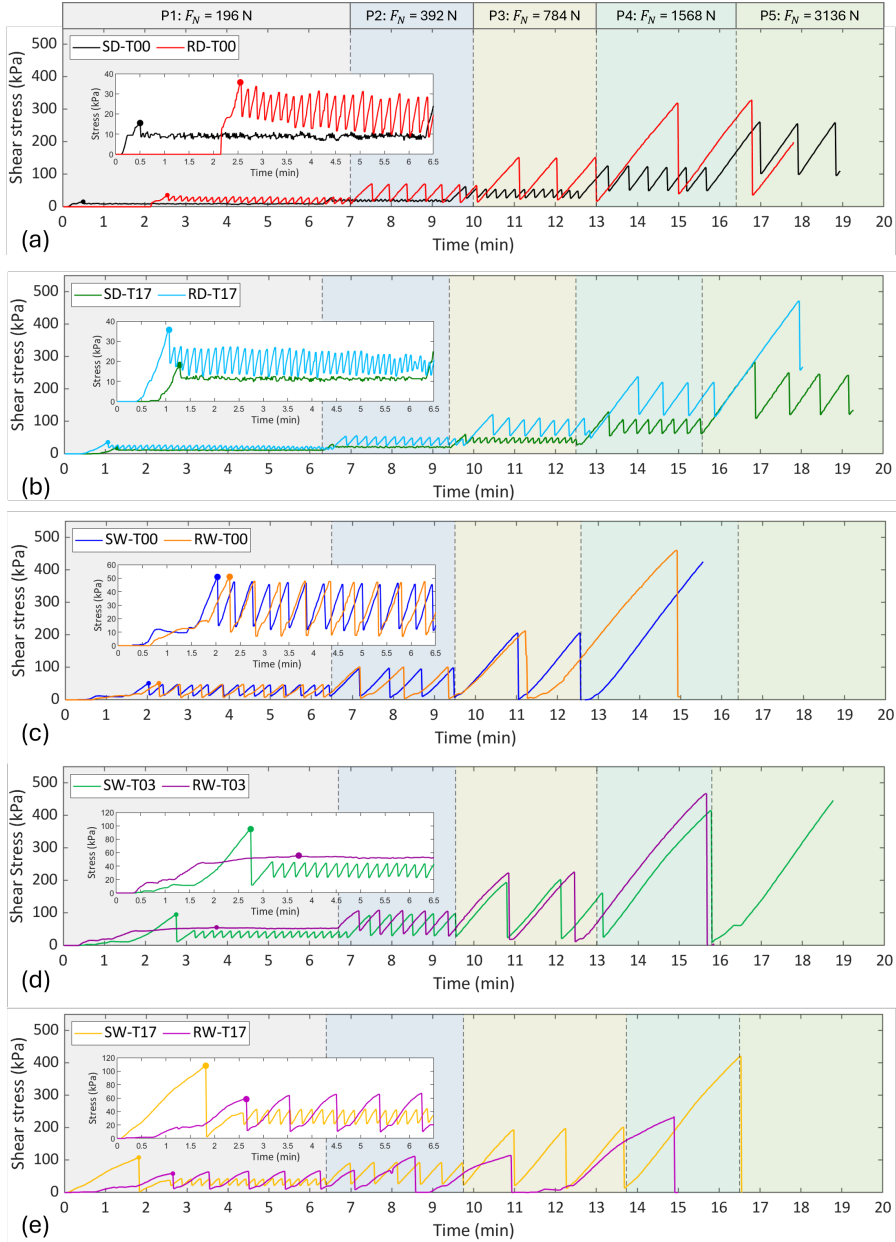


Figure 4.3. Shear stress vs. shearing time for (a) SD-T00 vs. RD-T00, (b) SW-T00 vs. RW-T00, (c) SW-T03 vs. RW-T03, (d) SD-T17 vs. RD-T17, and (e) SW-T17 vs. RW-T17, with circles marking healing strength.

4.3.2 Friction angle

Figure 4.4 (a) and (b) shows the residual friction angle of all samples. In dry unhealed samples, the friction angle is between 5.4° and 16.1° for smooth fracture surfaces (SD-T00), about twice lower compared to rough sample RD-T00 ($3.3^\circ - 33.8^\circ$). Following 17 days of dry healing, the friction angle of both the smooth and rough sample is unchanged, based on the average values of low and high residual friction angles (Figure 4.4 (c)). Overall, rough surfaces exhibit friction angles approximately twice as high as smooth surfaces, regardless of healing time. All wet samples exhibit friction angles between ranging from 0 and 44° , regardless of surface roughness levels or healing time. Wet unhealed samples with smooth surfaces (SW-T00, 0° to 41.5°) exhibit a friction angle twice as high as their dry counterparts (SD-T00, 5.4° to 16.1°), whereas rough fracture surfaces, exhibit more similar friction angles for dry and wet samples (Figure 4.4 (c)).

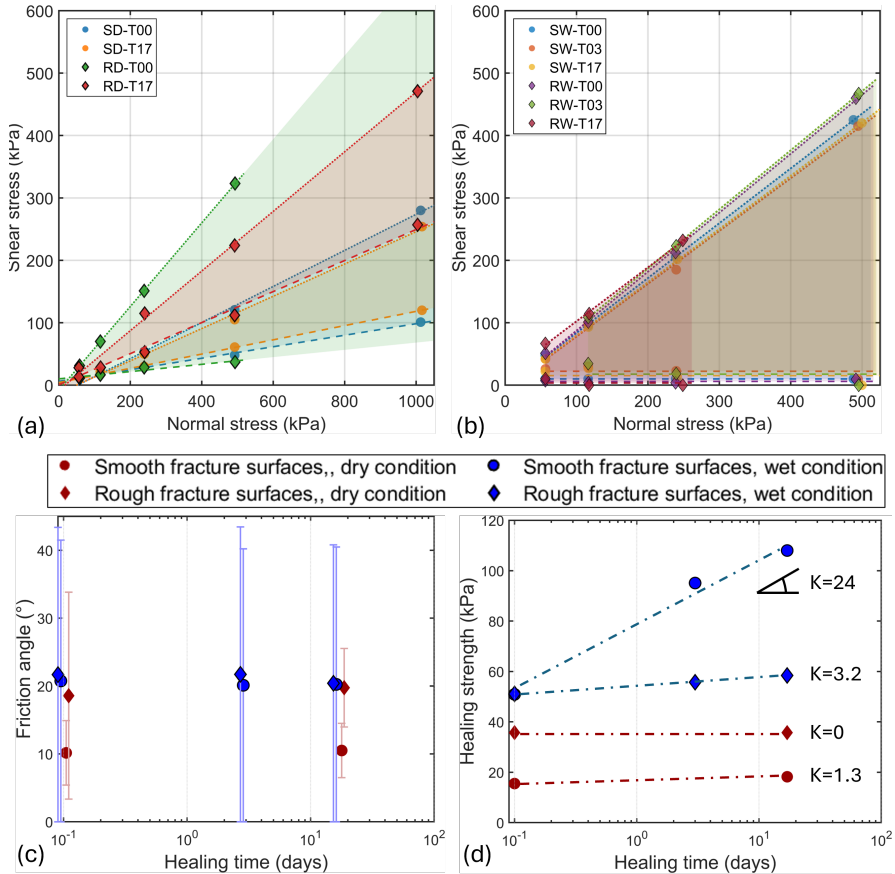


Figure 4.4. Normal stress versus shear stress, with the best-fit line representing the Mohr-Coulomb criterion for dry samples (a) and wet samples (b). For each sample, the upper dashed line corresponds to the maximum shear stresses, while the lower dashed line (same colour) corresponds to the minimum

shear stresses, both plotted against their respective normal stresses. The shaded area between the two lines indicates the range of residual friction angles. (c) Residual friction angle versus healing time for dry (red bars) and wet (blue bars) samples, showing the ranges defined in (a) and (b). Red diamonds and circles (dry) and blue diamonds and triangles (wet) denote the average values between the lower and upper friction angles. (d) Healing strength versus healing time for all samples, the value of “k” represents the slope of the fitting curves, expressed in kPa/Lg(day).

4.3.3 Microstructural analysis

The 3D profiles of the fracture surfaces obtained using a digital microscope are presented in Figure 4.5. The fracture surfaces before shearing exhibit uneven topography with visible scratches (Figure 4.5 (a)-(b)). The smooth surface (Figure 4.5 (a)) shows a higher density of scratches compared to the rough surface (Figure 4.5 (b)). Figure 4.5 (c) - (f) display the representative surfaces after shearing. Notably, the surface of the non-healed dry sample shows minimal changes after shearing compared to its pre-shearing state and is therefore not displayed. In contrast, the dry sample healed for 17 days exhibits striations after shearing (Figure 4.5 (c)-(d)), regardless of the initial roughness.

In contrast, for wet healed samples Figure 4.5 (e) and (f) reveal the development of shiny cubic grains on the fracture surface, interpreted to be crystal growth on the fracture walls after 17 days of wet healing. The smooth sample (Figure 4.5 (e)) shows on average larger grains than the rough sample (Figure 4.5 (f)). Quantitatively, we examine the line roughness (R_q) of the fracture surface along the shear direction before healing and after shearing (see Figure 4.6). After shearing, the roughness increases compared to before shearing, except for RD-T00, though there are no obvious trends with healing time or the presence or absence of fluid.

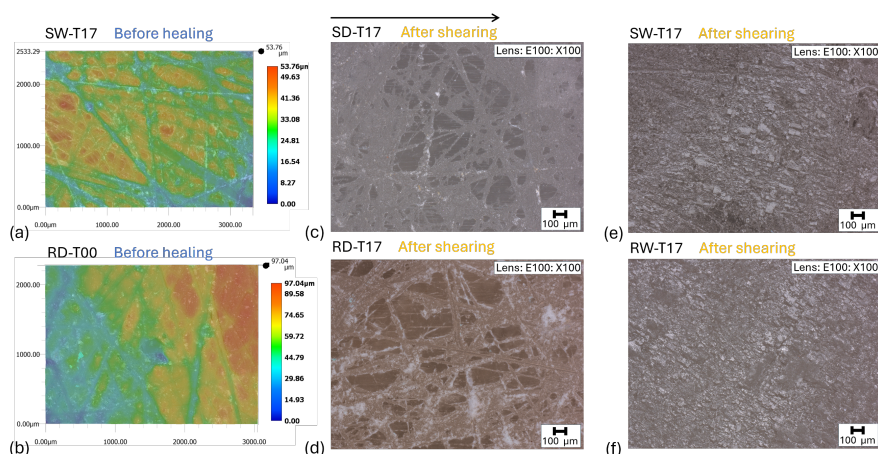


Figure 4.5. (a) and (b) show 3D profiles of the fracture surfaces for SW-T17 and RD-T00 before healing, with the unit in the plot being μm . (c) and (d) show the fracture surfaces of SD-T17, RD-T17, SW-T17, and RW-T17 after shearing, all at 100 $\times$ magnification lens. The arrow indicates the shearing direction.

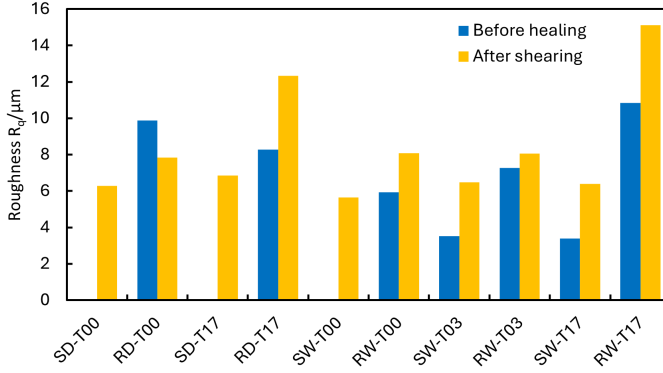


Figure 4.6. The roughness of different samples is presented. However, roughness is not measured before healing for SD-T00, SD-T17, and SW-T00.

4.4 Discussion and conclusions

This study investigates the healing behaviour of rock salt fractures under varying initial fracture roughness and healing conditions. In dry conditions, samples with smooth fracture surfaces show limited strength recovery, with healing strength increasing modestly from 15 kPa to 18 kPa after 17 days, while rough-surfaced samples exhibit no measurable improvement. The smooth and rough healed samples exhibit striations after shearing (Figure 4.4 (a)), while the non-healed samples lack distinct microstructural features. This suggests some activity has taken place on the fracture surface during the healing process. We attribute the mild strength recovery and striations to a healing mechanism primarily driven by plastic deformation caused by dislocations (Houben et al., 2012). We hypothesize that longer healing durations would lead to a clearer time-dependent recovery for dry samples. Additionally, samples with rough fracture surfaces exhibit an enhanced initial mechanical locking effect. Consequently, the friction angle of rough-surfaced samples is twice as high as that of smooth-surfaced samples, as confirmed by the high roughness levels observed in dry samples with rough fracture surfaces (Figure 4.4 (b)).

In contrast to the dry samples, the wet samples with smooth and rough surface exhibit a clear log-linear dependence on healing time, where the log-linear slope for smooth samples is 7.5 times higher compared to rough samples (Figure 4.4 (a)). The enhanced healing observed in wet samples compared to dry samples aligns with findings from Salzer et al. (2007) and Li et al. (2024), which attributed strength restoration to the recrystallization process. Our microstructural observations support these findings, showing clear evidence of recrystallization on fracture surfaces after 17 days of wet healing. Houben et al. (2012) infer that the crystallization process involves the migration of fluid-filled fracture boundaries, leading to the overgrowth of fractures and the formation of sub-spherical fluid inclusions. Similarly, Ji et al. (2022) through microstructural observations, note that fracture surfaces tend to evolve into low-energy (100) crystal forms, transforming the fracture space into less well-connected arrays of pore inclusions. The higher rate of strength recovery observed in wet samples with

smooth surfaces compared to those with rough surfaces can be attribute to differences in effective contact area. Smooth fracture surfaces provide a larger effective contact area, facilitating more efficient recrystallization. In contrast, rough surfaces are characterized by larger apertures, which impedes the recrystallization process by restricting crystal growth across the fracture space. This prevents the formation of "bridges" between opposing surfaces and thereby limits the recovery of mechanical strength (Li et al., 2024). The better connection between the fracture halves for smooth surfaces is shown by the observed bigger crystal size post-shearing for smooth wet surfaces (Figure 4.5 (e)-(f)). However, even though recrystallization and an increase in the roughness of post-shearing fracture surfaces are observed, the friction angle of all wet samples remains consistent. We interpret this as the solution within the fracture space being the main agent influencing the shear stress response. This effect is likely driven by a combination of factors, including the solution's viscosity, the surface tension and any potential adhesion between the solution and the rock salt fracture walls. These findings advance the understanding of roughness, solution, and time-dependent changes in strength recovery. Our results show there is a clear inhibitory effect of surface roughness on the time-dependent recovery, even for fully wet surfaces.

4.5 References

- Bos, B., Peach, C.J. and Spiers, C.J., 2000. Slip behavior of simulated gouge-bearing faults under conditions favoring pressure solution. *Journal of Geophysical Research: Solid Earth*, 105(B7), pp.16699-16717. <https://doi.org/10.1029/2000JB900089>
- Bos, B.A.R.T. and Spiers, C.J., 2002. Fluid-assisted healing processes in gouge-bearing faults: Insights from experiments on a rock analogue system. *Pure and Applied Geophysics*, 159(11), pp.2537-2566. <https://doi.org/10.1007/s00024-002-8747-2>
- Desbois, G., Urai, J.L., Kukla, P.A., Wollenberg, U., Pérez-Willard, F., Radf, Z., Riholm, S., 2012. Distribution of brine in grain boundaries during static recrystallization in wet, synthetic halite: Insight from broad ion beam sectioning and SEM observation at cryogenic temperature. *Contributions to Mineralogy and Petrology*, 163, 19–31. <https://doi.org/10.1007/s00410-011-0656-x>
- Dieterich, J.H. and Kilgore, B.D., 1994. Direct observation of frictional contacts: New insights for state-dependent properties. *Pure and applied geophysics*, 143, pp.283-302. <https://doi.org/10.1007/BF00874332>
- Dieterich, J.H., 1972. Time-dependent friction in rocks. *Journal of Geophysical Research*, 77(20), pp.3690-3697. <https://doi.org/10.1029/JB077i020p03690>
- Fuenkajorn, K. and Phueakphum, D., 2011. Laboratory assessment of healing of fractures in rock salt. *Bulletin of Engineering Geology and the Environment*, 70, pp.665-672. <https://doi.org/10.1007/s10064-011-0370-y>
- Houben, M.E., Ten Hove, A., Peach, C.J. and Spiers, C.J., 2013. Crack healing in rocksalt via diffusion in adsorbed aqueous films: Microphysical modelling versus experiments. *Physics and Chemistry of the Earth, parts A/B/C*, 64, pp.95-104. <https://doi.org/10.1016/j.pce.2012.10.001>
- Ji, Y., Spiers, C.J., Hangx, S.J.T., de Bresser, J.H.P. and Drury, M.R., 2022. 4D microtomography of brine-assisted healing processes in deformation-damaged rocksalt: A first look. In *The Mechanical Behavior of Salt X* (pp. 88-97). CRC Press. <https://doi.org/10.1201/9781003295808-9>
- Kanagawa, K., Cox, S.F. and Zhang, S., 2000. Effects of dissolution-precipitation processes on the strength and mechanical behavior of quartz gouge at high-temperature hydrothermal conditions. *Journal of Geophysical Research: Solid Earth*, 105(B5), pp.11115-11126. <https://doi.org/10.1029/2000JB900038>
- Karner, S.L., Marone, C. and Evans, B., 1997. Laboratory study of fault healing and lithification in simulated fault gouge under hydrothermal conditions. *Tectonophysics*, 277(1-3), pp.41-55. [https://doi.org/10.1016/S0040-1951\(97\)00077-2](https://doi.org/10.1016/S0040-1951(97)00077-2)
- Kishida, K., Yano, T. and Yasuhara, H., 2012, October. Healing and shear stress reduction of rock salt single fracture under slide-hold-slide direct shear experiments. In *ISRM International Symposium-Asian Rock Mechanics Symposium* (pp. ISRM-ARMS7). ISRM.
- Li, Z., Kang, Y., Fan, J., Fourmeau, M., Chen, J., Jiang, D. and Nelias, D., 2024. Macroscopic experimental study and microscopic phenomenon analysis of damage self-healing in salt rock. *Engineering Geology*, 338, p.107634. <https://doi.org/10.1016/j.enggeo.2024.107634>
- Niemeijer, A., Marone, C., Elsworth, D., 2008. Healing of simulated fault gouges aided by pressure solution: Results from rock analogue experiments. *Journal of Geophysical Research: Solid Earth*, 113(B4). <https://doi.org/10.1029/2007JB005376>
- Peach, C.J., 1991. Influence of deformation on the fluid transport properties of salt rocks.
- Pluymakers, A.M.H., Niemeijer, A.R., 2015. Healing and sliding stability of simulated anhydrite fault gouge: Effects of water, temperature and CO₂. *Tectonophysics*, 656, 111–130. <https://doi.org/10.1016/j.tecto.2015.06.012>
- Renard, F., Beauprêtre, S., Voisin, C., Zigone, D., Candela, T., Dysthe, D.K., Gratier, J.P., 2012. Strength evolution of a reactive frictional interface is controlled by the dynamics of contacts and chemical effects. *Earth and Planetary Science Letters*, 341–344, 20–34. <https://doi.org/10.1016/j.epsl.2012.04.048>
- Renard, F., Bernard, D., Thibault, X., Boller, E., 2004. Synchrotron 3D microtomography of halite aggregates during experimental pressure solution creep and evolution of the permeability. *Geophysical Research Letters*, 31(7). <https://doi.org/10.1029/2004GL019605>
- Salzer, K., Popp, T. and Böhnel, H., 2017. Mechanical and permeability properties of highly pre-compacted granular salt bricks. In *The Mechanical Behavior of Salt-Understanding of THMC Processes in Salt* (pp. 239-248). CRC Press.
- Sutherland, H.J. and Cave, S.P., 1980, October. Argon gas permeability of New Mexico rock salt under hydrostatic compression. In *International journal of rock mechanics and mining sciences & geomechanics abstracts* (Vol. 17, No. 5, pp. 281-288). Pergamon. [https://doi.org/10.1016/0148-9062\(80\)90810-4](https://doi.org/10.1016/0148-9062(80)90810-4)
- Van den Ende, M.P.A., Niemeijer, A.R., 2019. An investigation into the role of time-dependent cohesion in interseismic fault restrengthening. *Science Report* 9, 9894. <https://doi.org/10.1038/s41598-019-46241-5>
- Zhang, L., Ren, G., Ge, Y., Zhang, C., Chu, F., 2024. Damage Self-Healing Property of Dissolved Salt Columns in Solid Potash Mine. *ACS Omega* 9(28), 31136–31147. <https://doi.org/10.3390/technologies13020060>

5. Analysis of rock salt healing within a cohesive zone modelling framework.

Abstract: *In the finite element method, zero-thickness interface elements are widely used to simulate fracturing processes. These elements, particularly those with elastoplastic constitutive laws, account for the reduction of material strength parameters due to mechanical work during fracturing. In this chapter, we use an existing constitutive law to incorporate time-dependent healing effects of rock salt fractures. Fracture initiation is described by a hyperbolic yield surface in the σ_n - τ_s stress plane, whose contraction is governed by a history variable representing dissipated fracture work. Healing is introduced as a time-dependent external factor, represented by the recovery of tensile strength, cohesion, or friction coefficient. For dry and wet samples, the increase in mechanical properties is described through assumptions derived from experimental observations. For verification and validation of the existing constitutive law, single-element simulations are performed under pure tension, pure shear, and combined compression–shear conditions, showing good agreement with analytical solutions. The model is then validated against non-healed samples, accurately reproducing the peak shear stress, the subsequent stress drop, and the final residual shear stress. The interface model further reproduces the peak shear stress and residual state of dry and wet healed samples, as well as the experimentally observed log-linear increase in peak shear stress with healing time. Long-term simulations further indicate a continued increase in shear strength, although the effect becomes negligible over extended timescales.*

5.1 Introduction

Rock salt formations are widely regarded as one of the most suitable geological media for the long-term underground storage of gases and disposal of radioactive waste (Chan et al., 2001; Leigh et al., 2011; Liu et al., 2023). Their mechanical stability permits the construction and operation of caverns that preserve structural integrity over extended periods (Groenenberg et al., 2020). However, fractures can develop and evolve in the damage zone surrounding salt caverns throughout their lifetime, due to hydraulic, thermal, and mechanical alternations, potentially compromising long-term safety (Bérest et al., 2001; Siemann et al., 2019). Conversely, the healing capacity of rock salt (i.e., the restoration of strength along pre-existing fractures) can contribute to the stability of salt caverns (Salzer et al., 2007; Li et al., 2024). Since the strength recovery of rock salt fractures evolves over extended period, accurately modelling long-term healing over years to decades is essential to ensure the reliability of salt-based storage systems. This chapter examines whether the shear stress response and recovery of rock salt fractures can be represented using the interface model proposed by Caballero et al. (2008), incorporating a time-dependent healing function. The performance of this constitutive model is evaluated through simulations of the shear box experiments described in Chapter 3, which revealed the following key characteristics of the mechanical behaviour of rock salt fractures:

- 1) The shear stress–shear displacement curve displays a distinct peak, followed by a softening stage until the shear stress reaches a residual level (Chapter 3, Figure 3.8).
- 2) The time-dependent recovery of shear strength exhibits a log-linear relationship with time. Wet samples follow a similar log-linear trend, with the presence of brine accelerating the healing process (Chapter 3, Figure 3.9).
- 3) In dry samples, the friction coefficient increases with healing time; in wet samples, the friction angle remains relatively constant but higher than in dry samples (Chapter 3, Table 3.1).

Fractures or discontinuities in materials are commonly modeled using interface elements, which can be embedded between continuum elements to simulate displacement jumps associated with fractures (Carol et al., 2001; Chen et al., 2009; Garagash, 2019; Martínez et al., 2022; Liaudat et al., 2023). Among these, zero-thickness interface elements are widely used to represent rock discontinuities, such as fractures, faults, and joints, without explicitly modeling their physical thickness. These elements are typically defined by pairs of coincident nodes on either side of the discontinuity and are known to be well suited for capturing the mechanical behavior of small-aperture fractures (Goodman et al., 1968; Garolera et al., 2020).

The cohesive zone model (CZM) is a constitutive framework used to describe the mechanical behavior of material interfaces or fractures (Dugdale, 1960; Barenblatt, 1962; Elices et al., 2002; Volokh et al., 2004; Taleghani et al., 2018). The widely adopted CZM defines the traction–separation relationship with an initial linear elastic response followed by a linear or non-linear softening phase, capturing damage initiation and progressive degradation until complete failure (Cendón et al., 2000; Ruiz et al., 2001). However, they often neglect frictional effects between fracture surfaces, resulting in zero residual shear stress after full separation based on the traction–separation law. Moreover, peak shear stress in these models that are independent of normal stress, which

contradicts observations from shear box tests. Consequently, CZM formulations incorporate explicit friction along fracture surfaces. To address this limitation, Alfano et al. (2006) developed a CZM framework that integrates Crisfield's interface-damage model with a Coulomb friction law; in this approach, friction is mobilized only after full decohesion, so shear resistance increases progressively as damage accumulates. Gao et al. (2021) proposed a CZM-based approach in which rock failure initiates according to the Mohr–Coulomb criterion, with Coulomb friction activated after complete decohesion. Zou & Hameed (2018) showed that damage–friction formulations in ABAQUS are highly sensitive to interface stiffness, as a single damage parameter governs both stiffness degradation and damage growth. To address this, they introduced an energy-based coupling linked to the cohesive energy release rate, making the model largely stiffness-independent beyond a certain stiffness threshold. Additionally, an elasto-plastic CZM introduced by Caballero et al. (2008) features a hyperbolic yield surface that triggers fracture under combined compression–shear loading. This formulation reproduces the shear response's dependence on normal stress and captures the residual shear-stress plateau that emerges after peak strength. The present chapter builds upon this constitutive law.

Healing has been incorporated into CZMs in various ways. Alsheghri and Abu Al-Rub. (2015, 2016) developed a thermodynamically consistent cohesive zone healing model (CZHM) for self-healing materials, introducing internal state variables that progressively restore interface stiffness and strength with time, temperature, and compressive stress. Ponnusami et al. (2018) modified the bilinear CZM to include a healing variable, enabling the interface to switch between intact and healed branches so fractures can repeatedly open, close, and heal, thus capturing multiple self-healing cycles. Schimmel and Remmers (2006) extended the CZM by dividing the stiffness of the interface element into damaged and undamaged components. The stiffness of the damaged component can recover over time according to a healing function, and the total stiffness is computed as the sum of contributions from both components. Similarly, a damage-healing CZM was developed by Freeman et al. (2020) by introducing a space and time dependent healing function. Based on this, a recovery term was added to the CZM, allowing the interface stiffness to be gradually restored. In many CZMs that incorporate healing effects, the mechanical properties of the healed region are assumed to fully recover to those of the intact material, a condition rarely achieved in natural rock fractures. Moreover, studies specifically addressing the healing behaviour of rock salt fractures remain limited, and the long-term recovery of mechanical properties, spanning years to decades, is often oversimplified. A constitutive model capable of capturing the evolution of mechanical properties due to both damage and healing is essential.

To this end, we explore here if we can use the elasto-plastic cohesive zone model originally proposed by Caballero et al. (2008), where fracture initiation is governed by a hyperbolic yield surface that progressively softens as a function of a history variable representing the accumulated fracture work energy. As this variable increases, three key mechanical parameters, namely the tensile strength, friction coefficient and cohesion, gradually decrease, reflecting interface degradation. To incorporate healing behaviour into the constitutive law, an external variable is introduced to describe the time-dependent recovery of these parameters using a log-linear function of time. The yield surface is expanded to represent the post-healing state. Experiments from Chapter 3 on

non-healed and healed samples are used to assess whether the constitutive law proposed by Caballero et al. (2008), combined with this extension, can reproduce the experimental results. Additional simulations are then performed to examine the long-term mechanical recovery over timescales of years to decades.

5.2 Elasto-plastic cohesive zone model of Caballero et al. (2008)

5.2.1 Model formulation

5.2.1.1 Basic variables

In two dimensions, the CZM proposed by Caballero et al. (2008) is formulated in terms of one normal and one tangential surface traction, $\boldsymbol{\sigma} = [\sigma_n, \tau_s]^T$ (T : transpose, σ_n and τ_s denote the normal and shear stresses, respectively), and the corresponding relative separation displacement $\mathbf{u} = [u_n, u_s]^T$ (Figure 5.1). Prior to fracture initiation, the interface element is assumed to exhibit elastic behaviour, assuming decoupling of the normal and tangential stiffness properties (Eq. (5.1)).

$$\mathbf{K} = \begin{bmatrix} k_n & 0 \\ 0 & k_s \end{bmatrix} \quad (5.1)$$

Where $\mathbf{K}$ denotes the stiffness matrix of the interface element, and k_n and k_s represent the normal and shear components of stiffness, respectively. The stiffness is assumed to remain constant under both compressive and tensile loading. Within the elastic domain, the constitutive relation for the interface element is expressed as $\boldsymbol{\sigma} = \mathbf{K}\mathbf{u}$.

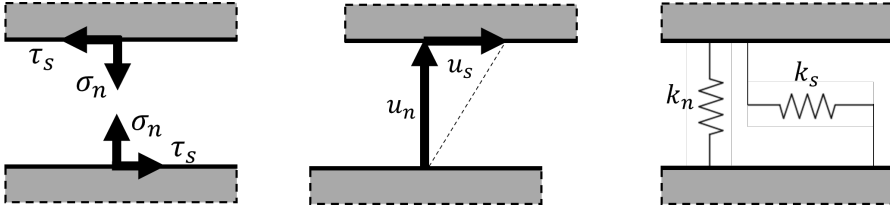


Figure 5.1. Definition of stress variable and relative displacement for the interface element.

Upon fracture, the deformation transitions into the plastic regime, and the total displacement vector is decomposed into elastic and plastic components (Eq. (5.2)).

$$\mathbf{u} = \begin{bmatrix} u_n \\ u_s \end{bmatrix} = \mathbf{u}^e + \mathbf{u}^p = \begin{bmatrix} u_n^e \\ u_s^e \end{bmatrix} + \begin{bmatrix} u_n^p \\ u_s^p \end{bmatrix} \quad (5.2)$$

where u_n and u_s denote the total displacement in the normal and tangential directions, respectively. $\mathbf{u}^e = [u_n^e, u_s^e]^T$ and $\mathbf{u}^p = [u_n^p, u_s^p]^T$ represent the elastic and plastic displacement components. Specifically, u_n^e and u_s^e are the elastic displacements in the normal and tangential directions, while u_n^p and u_s^p correspond to the plastic displacements in the respective directions.

The zero-thickness interface element represents the fracture process zone rather than a physical layer. Therefore, its elastic deformation should be minimal to prevent artificial interpenetration or sliding before fracture initiation. To achieve this, the elastic normal and shear stiffness must be assigned very high values. However, excessively large stiffness can lead to numerical problems, such as ill conditioning of the global stiffness matrix due to strong stiffness contrasts. It can also cause significant deviations in the elastic trial stress from the yield surface, resulting in instability during the plastic return process. To ensure both numerical stability and physical accuracy, the elastic stiffness should be large enough to suppress elastic deformation but not so large that it compromises computational performance (Caballero et al., 2008; Cerfontaine et al., 2015).

5.2.1.2 Yield surface and potential surface

The yield surface F adopted in this paper is the hyperbolic surface proposed by Caballero et al. (2008). It is depicted in Figure 5.2 and defined in Eq. (5.3).

$$F(\boldsymbol{\sigma}, \boldsymbol{\varphi}) = -C - \sigma_n \tan \phi + \sqrt{\tau_s^2 + (C - \chi \tan \phi)^2} = 0 \quad (5.3)$$

where $\boldsymbol{\varphi} = [\chi, C, \tan \phi]$ is the vector of tensile strength χ , cohesion C and friction coefficient $\tan \phi$.

Based on the characteristics of a hyperbolic curve, the tensile strength χ is abscissa of the hyperbola. The apparent cohesion C and friction coefficient $\tan \phi$ are the last two variables defining the asymptote to the hyperbola. These three hardening variables (i.e., $[\chi, C, \phi]$) control the shape of hyperbolic yield surface ($F = 0$).

In our experimental study, the vertical displacement during shearing is minimal, indicating negligible dilatational behaviour (Chapter 3, Figure 3.4). In plasticity theory, the flow rule defines the direction of plastic strain development once the material reaches the yield surface (Bland et al., 1957). Given the absence of significant volumetric change, an associated flow rule is adopted, where the plastic potential surface coincides with the yield surface ($Q = F = 0$).

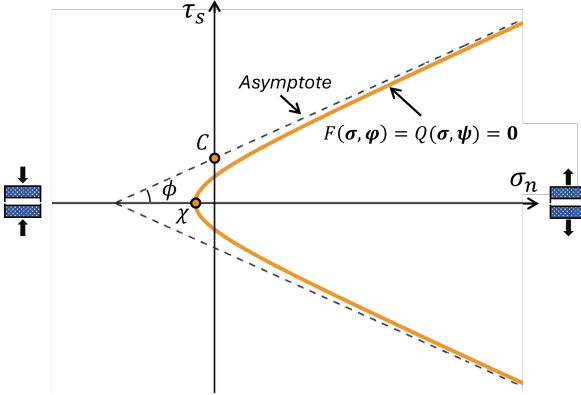


Figure 5.2. Hyperbolic yield surface and plastic potential surface ($F = Q = 0$). Compressive stress is defined as positive, and tensile stress as negative.

5.2.1.3 History variables

The evolution of the hyperbolic yield surface is controlled by three parameters: the tensile strength, cohesion, and friction coefficient. These parameters depend on an internal history variable (W_{cr}), which represents degradation resulting from the fracture process. This variable is defined as a function of the work dissipated during fracture damage evolution, with its incremental form given in Eq. (5.4).

$$dW_{cr} = \begin{cases} \sigma_n du_n^p + \tau_s du_s^p & , \sigma_n < 0 \text{ (tension)} \\ (|\tau_s| + \sigma_n \tan \phi) du_s^p & , \sigma_n \geq 0 \text{ (compression)} \end{cases} \quad (5.4)$$

For tensile loading (Mode I), damage accumulates until the interface fails when the accumulated energy reaches G_F^I (fracture energy in the normal direction). For compression–shear loading (Mode II), the interface fails once the accumulated energy reaches G_F^{II} (fracture energy in the tangential direction). It is important to note that the measured dissipation includes a substantial frictional component converted to heat; because this portion does not contribute to fracture propagation, it must be subtracted from W_{cr} in Eq. (5.4) (Caballero et al., 2008; Martínez et al., 2022).

5.2.1.4 Evolution laws

As the interface degrades, the internal history variable increases. Correspondingly, the tensile strength, cohesion, and friction coefficient decrease with progressive fracturing. To describe this relationship in a general form, the evolution of χ , C and $\tan \phi$ is not defined in terms of W_{cr} , but in terms of two non-dimensional variables:

$$\xi_1 = \begin{cases} \frac{1}{2} - \frac{1}{2} \cos\left(\frac{\pi W_{cr}}{G_F^I}\right) & 0 \leq W_{cr} \leq G_F^I \\ 1, & W_{cr} > G_F^I \end{cases} \quad (5.5)$$

$$\xi_2 = \begin{cases} \frac{1}{2} - \frac{1}{2} \cos\left(\frac{\pi W_{cr}}{G_F^{II}}\right) & 0 \leq W_{cr} \leq G_F^{II} \\ 1, & W_{cr} > G_F^{II} \end{cases} \quad (5.6)$$

ξ_1 and ξ_2 range from 0 to 1. These two definitions avoid discontinuous derivatives at points $\xi_1 = \xi_2 = 0$ and $\xi_1 = \xi_2 = 1$.

The tensile strength χ decreases from its initial value χ_0 as the fracturing progresses. Once W_{cr} reaches G_F^I , the tensile strength is fully degraded, and the element can no longer resist any tensile force. This behaviour is described by the following softening law:

$$\chi = (1 - \xi_1)\chi_0 \quad (5.7)$$

The cohesive strength during fracturing is given by C , here C_0 is initial cohesion:

$$C = (1 - \xi_2)C_0 \quad (5.8)$$

The friction coefficient diminishes from the initial value, $\tan \phi_0$, to the residual value, $\tan \phi_r$, which is expressed in Eq. (5.9):

$$\tan \phi = (1 - \xi_2)\tan \phi_0 + \xi_2 \tan \phi_r \quad (5.9)$$

When the W_{cr} is equal to G_F^{II} , the cohesion is reduced to zero and the friction coefficient decays to its residual value.

5.2.2 Numerical integration

5.2.2.1 Elastic predictor-plastic corrector strategy

This section outlines the numerical integration procedure performed by Caballero et al. (2008). Here, we provide a concise overview. The stress update process begins with an elastic predictor step, assuming a purely elastic fracture response over the current increment. Based on the known converged stress state at time step t and the incremental displacement obtained from the global structural analysis, the trial stress at time step $t + 1$ is computed using the elastic stiffness tensor (Eq. (5.10)). This trial stress serves as a provisional estimate and is evaluated against the yield criterion by substituting it into the yield function to determine whether the material point remains elastic or undergoes plastic deformation. If $F(\sigma_{trial}^{t+1}, W_{cr,trial}^{t+1}) < 0$, the trial stress state σ_{trial}^{t+1} is in the elastic regime. The stress and plastic work are updated to $\sigma^{t+1} = \sigma_{trial}^{t+1}$ and $W_{cr}^{t+1} = W_{cr,trial}^{t+1} = 0$. If $F(\sigma_{trial}^{t+1}, W_{cr,trial}^{t+1}) > 0$, a plastic corrector step is required to enforce consistency (yield surface $F = 0$) with the yield surface (Figure 5.3). In this case, the return mapping algorithm is employed within the framework of the backward Euler integration to update the stress, internal variables, and compute the plastic multiplier.

$$\sigma_{trial}^{t+1} = \sigma^t + K du^{t+1} \quad (5.10)$$

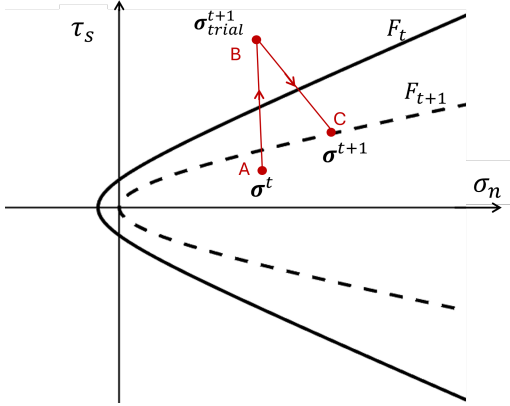


Figure 5.3. Schematic of the return mapping algorithm. Point A presents the converged stress state σ^t at time step t (elastic regime). Point B presents trial stress $\sigma^{t+1, trial}$ at $t + 1$ (outside of elastic regime). The updated yield surface F_{t+1} and must be projected back onto it to obtain the updated stress σ^{t+1} . Point C the final corrected stress after return mapping.

5.2.2.2 Backward Euler integration

When the incremental displacement at time step $t + 1$, denoted as $d\mathbf{u}^{t+1}$ involves inelastic behaviour, it is decomposed into elastic and plastic components as: $d\mathbf{u}^{t+1} = d[\mathbf{u}^e]^{t+1} + d[\mathbf{u}^p]^{t+1}$. This decomposition allows the stress at time $t + 1$ to be computed using the backward Euler integration scheme:

$$\sigma^{t+1} = \sigma^t + \mathbf{K}(d\mathbf{u}^{t+1} - d[\mathbf{u}^p]^{t+1}) = \sigma^t + \mathbf{K}d\mathbf{u}^{t+1} - \mathbf{K}d[\mathbf{u}^p]^{t+1} \quad (5.11)$$

The plastic component of the incremental displacement, $d\mathbf{u}^p$, is governed by the associated flow rule and is defined as:

$$d[\mathbf{u}^p]^{t+1} = d\lambda^{t+1} \left(\frac{\partial Q}{\partial \sigma} \right)^{t+1} = d\lambda^{t+1} \left(\frac{\partial F}{\partial \sigma} \right)^{t+1} = d\lambda^{t+1} [\mathbf{m}]^{t+1} \quad (5.12)$$

where Q is the plastic potential function, with $Q = F$, and $d\lambda^{t+1}$ is the incremental plastic multiplier. $\mathbf{m}$ represents the plastic flow direction.

Substituting this expression back into the stress update equation yields:

$$\sigma^{t+1} = \sigma^t + \mathbf{K}d\mathbf{u}^{t+1} - d\lambda^{t+1} \mathbf{K}[\mathbf{m}]^{t+1} \quad (5.13)$$

Similarly, the plastic work at time $t + 1$ is updated incrementally as:

$$W_{cr}^{t+1} = W_{cr}^t + dW_{cr}^{t+1} \quad (5.14)$$

To solve all unknown independent variables, including σ^{t+1} , W_{cr}^{t+1} and $d\lambda^{t+1}$, an additional equation is required. This is provided by the consistency condition, which ensures that the updated stress state remains on the yield surface:

$$F(\sigma^{t+1}, W_{cr}^{t+1}) = 0 \quad (5.15)$$

5.2.2.3 Newton-Raphson iteration

In the equations presented above, the unknown variables appear on both sides, indicating the necessity of an implicit solution strategy. A commonly adopted approach for solving such nonlinear systems, particularly those arising from constitutive integration and equilibrium equations in computational mechanics, is the Newton–Raphson (NR) method. This iterative technique is well-suited for use with implicit time integration schemes like the backward Euler method (Caballero et al., 2008). Within this context, the NR method is employed to enforce the consistency condition by solving for the unknowns at time step $t + 1$, specifically the stress, internal history variables, and the incremental plastic multiplier. At each iteration, the residuals are linearized using the Jacobian matrix, allowing for efficient convergence near the solution point. To begin, the residual vector corresponding to the nonlinear system of three equations is defined as:

$$\mathbf{r}^i = \mathbf{r}^i(\boldsymbol{\sigma}, W_{cr}, d\lambda) = \begin{cases} \boldsymbol{\sigma}^i + d\lambda^i \mathbf{K}[\mathbf{m}]^i - \boldsymbol{\sigma}^t - \mathbf{K} d\mathbf{u}^{t+1} \\ W_{cr}^i - W_{cr}^t - dW_{cr}^i \\ F(\boldsymbol{\sigma}^i, W_{cr}^i) \end{cases} \quad (5.16)$$

where i the iteration counter within the current time step between t and $t + 1$. The component of $\mathbf{r}$ are assembled from Eqs. (5.14) – (5.16). The iterative solution continues until convergence is achieved, as determined by evaluating the norm of the residual and comparing it to a predefined tolerance, set to $TOL = 10^{-5}$.

$$\|\mathbf{r}\| = \sqrt{(\mathbf{r}(\boldsymbol{\sigma}))^2 + (\mathbf{r}(W_{cr}))^2 + (\mathbf{r}(d\lambda))^2} < TOL \quad (5.17)$$

To solve the system, the residual is expanded in a Taylor series and truncated at the first-order term:

$$\mathbf{r}(\boldsymbol{\sigma} + \delta\boldsymbol{\sigma}, W_{cr} + \delta W_{cr}, d\lambda + \delta d\lambda) = \mathbf{r}(\boldsymbol{\sigma}, W_{cr}, d\lambda) + \frac{\partial \mathbf{r}(\boldsymbol{\sigma}, W_{cr}, d\lambda)}{\partial (\boldsymbol{\sigma}, W_{cr}, d\lambda)} \begin{pmatrix} \delta\boldsymbol{\sigma} \\ \delta W_{cr} \\ \delta d\lambda \end{pmatrix} + O[\delta^2] \quad (5.18)$$

Here, the Jacobian matrix $\mathbf{J}$ is defined as the matrix of partial derivatives of the residual with respect to the independent variables, evaluated at the current iteration:

$$\mathbf{J} = \frac{\partial \mathbf{r}(\boldsymbol{\sigma}, W_{cr}, d\lambda)}{\partial (\boldsymbol{\sigma}, W_{cr}, d\lambda)} = \begin{bmatrix} I + d\lambda \mathbf{K} \frac{\partial \mathbf{m}}{\partial \boldsymbol{\sigma}} & d\lambda \mathbf{K} \frac{\partial \mathbf{m}}{\partial W_{cr}} & \mathbf{K} \mathbf{m} \\ -\frac{\partial dW_{cr}}{\partial \boldsymbol{\sigma}} & 1 - \frac{\partial dW_{cr}}{\partial W_{cr}} & -\frac{\partial dW_{cr}}{\partial d\lambda} \\ \frac{\partial F}{\partial \boldsymbol{\sigma}} & \frac{\partial F}{\partial W_{cr}} & 0 \end{bmatrix} \quad (5.19)$$

By setting the residual to zero and neglecting higher-order terms (i.e., $O[\delta^2] \approx 0$), the linearized system becomes:

$$0 = \mathbf{r}(\boldsymbol{\sigma}^i, W_{cr}^i, d\lambda^i) + \frac{\partial \mathbf{r}(\boldsymbol{\sigma}^i, W_{cr}^i, d\lambda^i)}{\partial (\boldsymbol{\sigma}, W_{cr}, d\lambda)} \begin{bmatrix} \delta\boldsymbol{\sigma}^{i+1} \\ \delta W_{cr}^{i+1} \\ \delta d\lambda^{i+1} \end{bmatrix} \quad (5.20)$$

Solving the linearized system of equations yields the iterative updates for the variables:

$$\begin{bmatrix} \delta \sigma^{i+1} \\ \delta W_{cr}^{i+1} \\ \delta d\lambda^{i+1} \end{bmatrix} = -[J^i(\sigma, W_{cr}, d\lambda)]^{-1} r(\sigma^i, W_{cr}^i, d\lambda^i) \quad (5.21)$$

These increments are then added to the previous estimates to update the variables for the next iteration.

$$\begin{bmatrix} \sigma^{i+1} \\ W_{cr}^{i+1} \\ d\lambda^{i+1} \end{bmatrix} = \begin{bmatrix} \sigma^i \\ W_{cr}^i \\ d\lambda^i \end{bmatrix} + \begin{bmatrix} \delta \sigma^{i+1} \\ \delta W_{cr}^{i+1} \\ \delta d\lambda^{i+1} \end{bmatrix} \quad (5.22)$$

5.2.2.4 Consistent tangent operator

Quadratic convergence of the Newton–Raphson scheme requires the consistent tangent operator (CTO $\partial \sigma / \partial du$) since an elastic stiffness yields only linear convergence and may even diverge under softening or strong non-linearity (Caballero et al., 2008). In this work the CTO is assembled after the stress-return algorithm has converged, i.e., once the local residual in Eq. (5.18) vanishes. Constructing it involves linearizing that residual with respect to the displacement increment du , placing all terms at time step $t+1$ (denoted by the iteration t) on the left and the terms at time step t on the right.

$$\frac{\partial}{\partial du} \begin{bmatrix} \sigma^{t+1} + d\lambda^{t+1} K[m]^{t+1} \\ W_{cr}^{t+1} - dW_{cr}^{t+1} \\ F(\sigma^{t+1}, W_{cr}^{t+1}) \end{bmatrix} = \frac{\partial}{\partial du} \begin{bmatrix} \sigma^t + K du^{t+1} \\ W_{cr}^{t+1} \\ 0 \end{bmatrix} \quad (5.23)$$

On the left-hand side, the chain rule is used to differentiate the local equilibrium residual with respect to the primary variables.

$$\frac{\partial}{\partial(\sigma, W_{cr}, d\lambda)} \begin{bmatrix} \sigma^{t+1} + d\lambda^{t+1} K[m]^{t+1} \\ W_{cr}^{t+1} - dW_{cr}^{t+1} \\ F(\sigma^{t+1}, W_{cr}^{t+1}) \end{bmatrix} \begin{bmatrix} \left(\frac{\partial \sigma}{\partial du}\right)^{t+1} \\ \left(\frac{\partial W_{cr}}{\partial du}\right)^{t+1} \\ \left(\frac{\partial d\lambda}{\partial du}\right)^{t+1} \end{bmatrix} = \begin{bmatrix} K \\ 0 \\ 0 \end{bmatrix} \quad (5.24)$$

Recognizing that the first term in Eq. (5.25) represents the Jacobian $[J]$, the consistent tangent stiffness can then be written as:

$$\left[\frac{\partial \sigma^{t+1}}{\partial du^{t+1}} \right] = \begin{bmatrix} \left(\frac{\partial \sigma}{\partial du}\right)^{t+1} \\ \left(\frac{\partial W_{cr}}{\partial du}\right)^{t+1} \\ \left(\frac{\partial d\lambda}{\partial du}\right)^{t+1} \end{bmatrix} = ([J]^{-1})^{t+1} \begin{bmatrix} K \\ 0 \\ 0 \end{bmatrix} \quad (5.25)$$

5.2.3 Numerical verification and validation

5.2.3.1 Verification of constitutive law

Several numerical examples at the material-point level are presented in this section. Before fitting the experimental data of chapter 3, we performed several numerical examples to demonstrate the key features of the constitutive model of Caballero et al.

(2008), using the user-defined material subroutine (UMAT) implemented in ABAQUS 2019 by Nie et al. (2022). A single cohesive element model is used to examine the evolution of mechanical behaviour under various loading conditions, including pure tension, pure shear, and combined compression–shear. The geometry and boundary conditions of the models are illustrated in Figure 5.4. All nodes at the bottom are fully constrained in all translational (X, Y, and Z) and rotational degrees of freedom. A reference point (RP) is defined to apply the prescribed displacement velocity in either the tensile or shear direction and to facilitate the extraction of reaction forces for stress calculation.

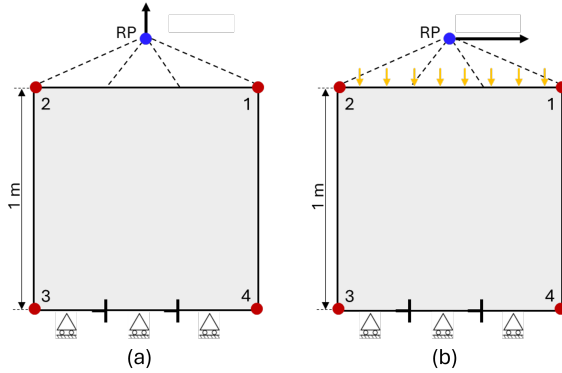


Figure 5.4. Boundary conditions for the 2D single-interface element: (a) uniaxial tension; (b) shear under compression. The blue point marks the reference point (RP), while the red points indicate nodes. The single element represents the interface element. Although its actual thickness is set to 1 m for visualization purposes, it can also be modelled as a zero-thickness element.

The parameters used in the tension test cases are adopted from Martínez et al. (2022), who employed the same constitutive law. These include a normal and shear stiffness $k_n = k_s = 1\text{E}8$ MPa/m, tensile strength $\chi_0 = 3$ MPa, cohesion $C_0 = 7$ MPa, initial friction coefficient $\tan \phi_0 = 0.8785$, residual friction coefficient $\tan \phi_r = 0.4$. Four pure tensile loading cases are examined to compare the constitutive responses under varying Mode I fracture energy values ($G_f^I = 30; 60; 90; 120$ N/m).

The resulting constitutive responses, expressed in terms of normal stress (σ_n) versus normal displacement (u_n), are shown in Figure 5.5 (a). Each $\sigma_n - u_n$ curve initially exhibits a steep linear-elastic response, followed by a nonlinear softening once the peak normal stress reaches initial tensile strength value ($\chi_0 = 3$ MPa). Beyond the peak stress, the history variable (W_{cr}) increases, indicating the progression of fracturing. By the end of loading, the interface element is fully degraded and can no longer sustain tensile stress. Additionally, increasing the fracture energy G_f^I from 30 to 120 N/m results in a more gradual reduction in tensile stress during the softening phase. The area under each $\sigma_n - u_n$ curve corresponding to the respective value of G_f^I . In the tensile test case with $G_f^I = 120$ N/m, the response is illustrated by points a–b–c–d–e. The initial state (point a) is characterized by zero tensile stress and normal displacement, lying within the elastic regime. As loading progresses, the normal stress reaches the peak tensile strength (point

b), marking the transition from the elastic to the plastic regime. The segment from the onset of softening (points b–c–d) represents the progressive degradation of the interface element, culminating in complete degradation at point e.

To verify that every stress state at the integration point lies on the yield surface, the evolution of the yield surface corresponding to points a–b–c–d–e is shown in Figure 5.5 (b). From point a to point b, the stress state remains within the elastic regime; therefore, the yield surfaces are identical, and the normal stress stays constant at -3 MPa, matching the initial tensile strength of 3 MPa. Beyond point b, the yield surface gradually shrinks as fracturing progresses, between points c and d, where the tensile stress decreases from 1.6 MPa to 0.4 MPa. At the final state (point e), the tensile stress approaches 0 MPa.

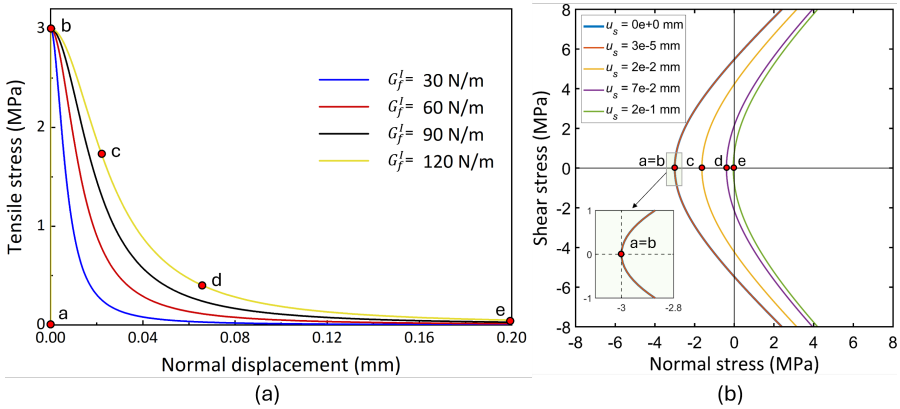


Figure 5.5 (a) Tensile stress–normal displacement responses with $G_f^I = 30; 60; 90; 120$ N/m. Red circles with black outlines mark points at different stages of the test with $G_f^I = 120$ N/m: point a - initial state; point b - peak normal stress, marking the onset of the fracturing process; points c and d - partially degraded states; and point e - fully damaged state. (b) Evolution of the yield surface for tension tests ($G_f^I = 120$ N/m), corresponding to points a–b–c–d–e in (a). The blue yield surface represents the initial condition. The orange yield surface corresponds to the peak normal stress (point b), which coincides with the initial yield surface (i.e., a=b in the inset). The green yield surface represents the fully degraded condition (point e).

The parameters used in compression–shear loading test are as follows: normal and shear stiffness $k_n = k_s = 1E7$ MPa/m, tensile strength $\chi_0 = 3$ MPa, cohesion $C_0 = 7$ MPa, initial friction coefficient $\tan \phi_0 = 0.6$, residual friction coefficient $\tan \phi_r = 0.4$, fracture energy $G_f^I = 30$ N/m and $G_f^{II} = 60$ N/m. Four cases are examined under different normal stress ($\sigma_n = 0; 1; 2; 3$ MPa).

The resulting shear stress – shear displacement ($\tau_s - u_s$) responses are shown in Figure 5.6 (a). In the pure shear case ($\sigma_n = 0$), the shear stress increases rapidly in the elastic regime until it reaches the initial yield surface ($F = 0$), corresponding to the peak shear stress. Beyond this point, continued shear displacement leads to degradation of interface element and a reduction in shear stress. As the interface becomes fully damaged, the residual shear stress approaches 0 MPa. When normal stress increases

from 1 to 2 and 3 MPa, the peak shear stress also increases due to the expansion of the initial yield surface ($F = 0$). Similarly, the residual shear stress rises from 0.4, 0.8 to 1.2 MPa consistent with the relation $\tau_r = \sigma_n \tan \phi_r$.

In Figure 5.6 (a), for the shear test case with $\sigma_n = 3$ MPa, points a and b represent the elastic regime, while points b–c–e show the progressive degradation of the interface element in the plastic regime. The corresponding yield surfaces are shown in Figure 5.6 (b). The stress state of points a and b share the same yield surface, as both lie within the elastic regime. By point d, compared to point c, both the tensile strength and cohesion have degraded and approach 0 MPa, resulting in a reduction of yield surface. As fracturing continues, the friction coefficient decreases until it reaches the residual value of 0.4 at point e, where both tensile strength and cohesion have fully diminished. At this residual stage, the yield surface reduces to the linear Mohr–Coulomb criterion, governed solely by frictional resistance.

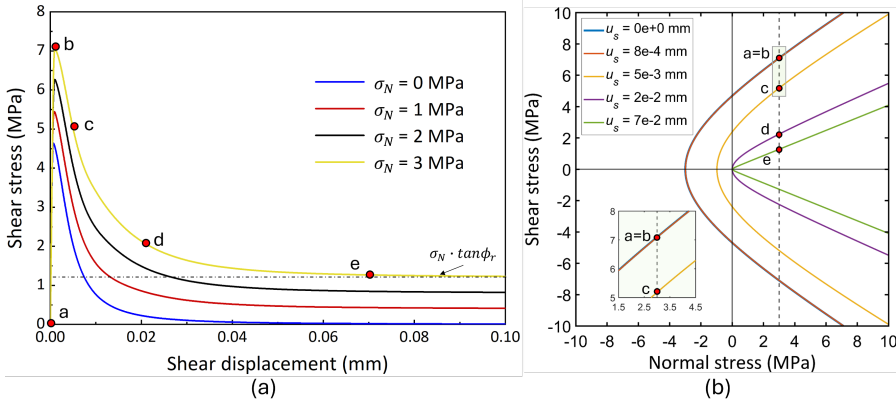


Figure 5.6. (a) Shear stress–shear displacement responses with $\sigma_n = 0; 1; 2; 3$ MPa. (b) Evolution of the yield surface for shear tests with $\sigma_n = 3$ MPa, corresponding to points a–b–c–d–e in (a). The dash line presents $\sigma_n \cdot \tan \phi_r = 3$ MPa.

5.2.3.2 Comparison with experimental results of non-healed salt samples

This section presents the validation of the constitutive law of Caballero et al. (2008) against the experimental data of this thesis. A finite element mesh is developed to replicate the sample dimensions and boundary conditions of the shear box experiments. Simulations are then performed to evaluate the model's ability to reproduce the mechanical behaviour observed in the non-healed samples, specifically D-T000 and W-T000, as described in Chapter 3.

The geometry and boundary conditions of the direct shear box test are shown in Figure 5.7. Rock salt is modelled in two dimensions (plane strain) using continuum CPS4R elements (four-node plane stress elements), while the fractures are represented by zero-thickness interface elements. The model consists of 1800 continuum elements governed by an elastic law and 60 interface elements. The interface elements are defined as

COH2D4, a two-dimensional four-node cohesive element with two integration points. Based on the experimental procedure, a shearing velocity of 0.5 mm/min is applied to the upper rock salt, and the normal stress is incrementally increased on its top surface. In the first loading stage (P1), the applied normal stress is 54.4 kPa, same with the experiments presented in chapter 3. All nodes at the bottom of the lower rock salt block are fully constrained in both translational (X, Y, and Z) and rotational degrees of freedom. The side boundaries of lower rock salt block are fixed in the X-direction.

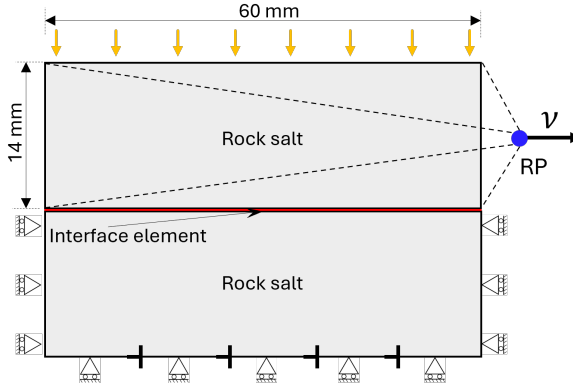


Figure 5.7. The geometry and boundary conditions of simulation model.

The shear stress response of sample D-T000 is first simulated. The missing mechanical properties of rock salt namely a Young's modulus of 2.5E4 MPa and a Poisson's ratio of 0.44, are obtained from the experimental study of Liang et al. (2007). To prevent interpenetration of the interface elements under normal stress, high normal and tangential elastic stiffness values of 1E5 MPa/m are assigned, i.e. exceeding the Young's modulus of the rock salt. For the dry sample D-T000, the two rock salt blocks are initially separated, indicating the absence of mechanical strength across the fracture. To represent this condition in the numerical model, the tensile strength and cohesion of the interface elements are assigned low values of 10 Pa and 20 Pa, respectively. Under these low tensile strength and cohesion conditions, the initial yield surface approximates a linear Mohr–Coulomb criterion. The initial friction coefficient is 0.285, obtained from the ratio of peak shear stress to normal stress in the D-T000 experiment. The residual values are 0.095 and 0.266, corresponding to high and low friction angles of 5.4° and 14.9°, respectively (Chapter 3, Table 3.1). The fracture energies in mode I and II are assigned values of $G_f^I = G_f^{II} = 2\text{E-}3 \text{ N/m}$ to best match the experimental results.

The numerical simulation results, with yellow representing case A with a high residual friction coefficient and red representing case B with a low coefficient, closely follow the experimental data (blue dashed line) across the five loading phases (P1 to P5) (See Figure 5.8 (a)). In stage P1, the initial shear stress increases sharply until the peak value τ_H is reached, followed by a stress drop and a plateau, accurately captured by the model.

During P2–P5, the simulations capture the progressive increase in shear strength with increasing normal stress.

The numerical results appropriately capture both the peak and residual shear stress observed in P1 (Figure 5.8 (b)). Additionally, Figure 5.8 (c) illustrates the evolution of the yield surface for simulation Case B in σ_n - σ_s space. The initial yield surface follows a linear Mohr–Coulomb criterion, with tensile strength and cohesion set close to zero. During the shearing process, the friction coefficient gradually decreases from 0.285 (initial friction coefficient) to 0.095 (residual friction coefficient), accompanied by a reduction in shear stress from 15.5 kPa to 5.2 kPa.

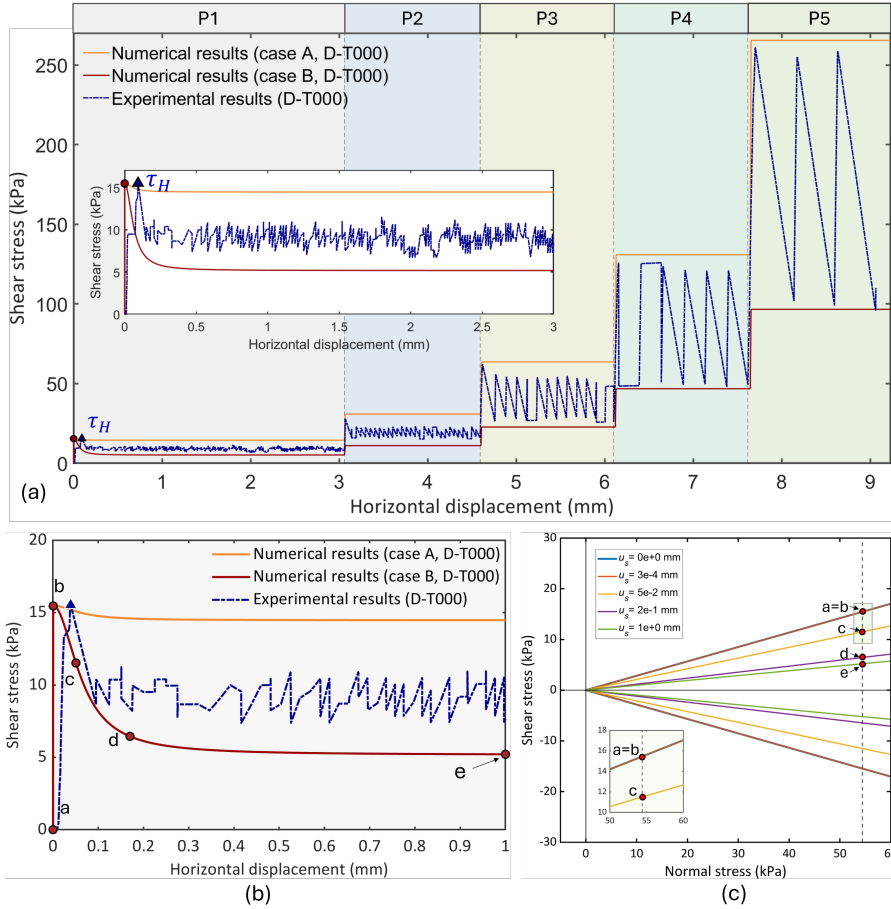


Figure 5.8. (a) Numerical and experimental shear stress–displacement response for the non-healed dry sample D-T000 over the full loading path; τ_H denotes the peak shear stress. For the experimental results, the initial loading phase (shear stress ≈ 0) prior to effective sample-shear box contact was omitted from the analysis to focus on the peak and residual shear stress responses; (b) Enlargement of the first 1 mm of displacement; (c) Evolution of the yield surface during P1 in simulation case B. The dashed line indicates the applied normal stress of 54.4 kPa.

Unlike the non-healed dry samples (D-T000), the initially wet samples exhibit measurable tensile strength and cohesion in rock salt fractures. This behaviour is attributed to the presence of saturated brine within the fracture, which may enhance interfacial bonding through mechanisms such as increased viscosity, surface tension, and potential adhesion. It is important to note that, due to the absence of direct measurements, several values needed to make the simulations run will be derived from observations and are approximations. For example, when one tries to pick up a set of blocks when saturated brine is present, when the upper rock salt block is picked up the lower block needs a few seconds before it detaches and falls. The mass of a single block is approximately 115 g, corresponding to a normal stress of 313 Pa. An initial tensile strength of 300 Pa is assumed accordingly. According to previous studies, the ratio of cohesion to tensile strength in brittle rocks such as sandstone ranges from 13 to 21 (Cai et al., 2009). In this study, a lower ratio of 5 is arbitrary adopted (i.e., $C_0/\chi_0 = 5$), which results in an estimated cohesion of 1500 Pa. The initial friction coefficient is set to 0.9, while the residual values are 0 and 0.885, corresponding to friction angles of 0° and 41.5° , respectively (following Chapter 3. Table 3.1). Fracture energies for Modes I and II are both assigned a value of $G_f^I = G_f^{II} = 0.2 \text{ N/m}$.

With these numbers, the peak shear stress from the numerical simulation (50.5 kPa) closely matches the experimental result (50.9 kPa) (Figure 5.9 (a)). Beyond the peak, the shear stress decreases, and the residual shear stress in the numerical model generally covers of the stress fluctuations observed in the experimental data. Figure 5.9 (b) illustrates the evolution of the yield surface in simulation case B. After reaching the peak shear stress at point b, the initially hyperbolic yield surface gradually contracts and transitions to a horizontal linear Mohr–Coulomb form at point e, corresponding to a residual friction coefficient of 0. The model therefore does not capture the stick–slip behaviour, as the focus of this study is on strength recovery rather than stress fluctuations.

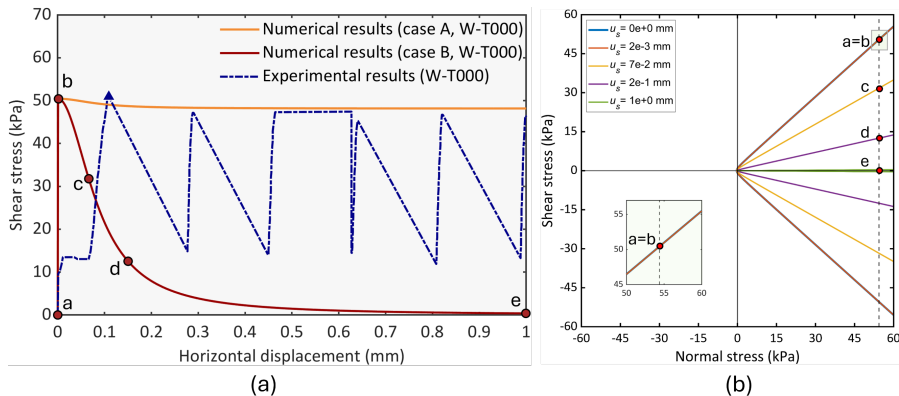


Figure 5.9 (a) Numerical and experimental shear stress–displacement curves within the initial 1 mm for the non-healed sample W-T000. The numerical results (case A and case B) use high and low residual friction coefficients, respectively, based on the experimental results reported in Chapter 3. (b) Evolution of the yield surface in simulation case B. The dashed line indicates the applied normal stress of 54.4 kPa.

5.2.4 Extension of the model of Caballero et al. (2008) to account for healing effect

We now attempt to incorporate the healing effect into the existing constitutive law following the proposed approach. This is done through introducing an external variable H_t , a time-dependent factor quantifying the mechanical restoration over time, where t is the healing time and $H_t \geq 1$ (reflecting the increase in strength with time). This variable directly enhances the initial mechanical properties, including the initial tensile strength χ_0 , initial cohesion C_0 , and initial friction coefficient $\tan \phi_0$. Specifically, after a given healing period, these properties are updated as $\chi_0(t) = H(t) \cdot \chi_0$, $C_0(t) = H(t) \cdot C_0$, $\tan \phi_0(t) = H(t) \cdot \tan \phi_0$. Consequently, the yield surface after healing expands and can then be expressed as:

$$F = -C_0(t) - \sigma_n \tan \phi_0(t) + \sqrt{\tau_s^2 + (C_0(t) - \chi_0(t) * \tan \phi_0(t))^2} = 0 \quad (5.26)$$

where, $\chi_0(t)$, $C_0(t)$ and $\tan \phi_0(t)$ represent the initial mechanical parameters after a healing period of time t .

This leads to the schematic presentation shown in Figure 5.10. Here, the initial stage (curve 1) corresponds to the yield surface, where the interface elements can sustain only limited shear and normal loads. Following a period of healing, the yield surface expands (curve 2), indicating increased shear and normal load capacities. Subsequently, it contracts due to shear or tensile damage of the interface elements (curve 3). In the residual stage, the interface elements lose their shear and tensile load capacities, leaving only frictional resistance.

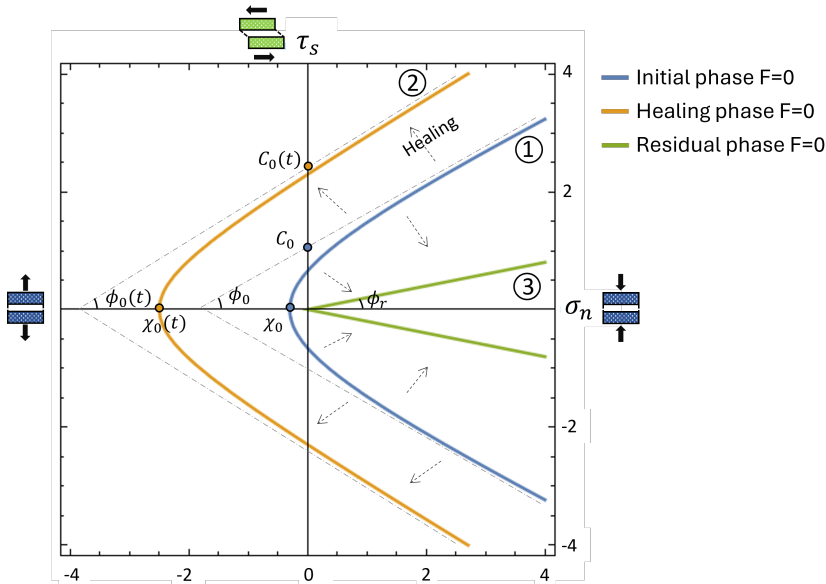


Figure 5.10 Diagram of yield surface evolution under healing and damage processes, showing expansion (curve 1 to curve 2) and shrinkage (curve 2 to curve 3).

In Figure 5.11, the mechanical response of interface with the healing effect is illustrated under stress–displacement conditions. After healing, three mechanical properties increase, and the fracture energies are enhanced according to H_t ($G_f^I(t) = G_f^I \cdot H(t)$, $G_f^{II}(t) = G_f^{II} \cdot H(t)$), where G_f^I and G_f^{II} are initial fracture energies, $G_f^I(t)$ and $G_f^{II}(t)$ are corresponding values after healing. With the expansion of the yield surface and the increase in fracture energy, the peak stresses in both the normal and shear directions increase (Figure 5.11 (a)–(b)).

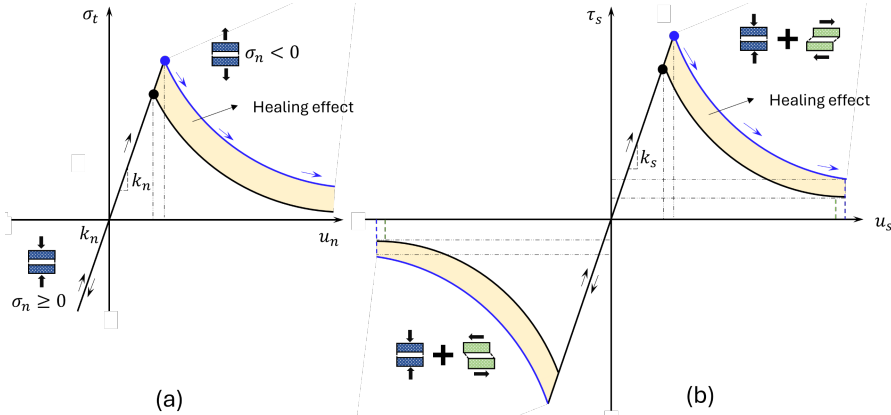


Figure 5.11. (a) shows the tensile stress (σ_t) – normal displacement (u_n) relationship under tensile test, (b) shear stress (τ_s) – shear displacement (u_s) relationship under pure shear and combined compression–shear test.

5.2.4.1 Comparison with experimental results of healed samples

Shear strength recovery in the shear box test exhibits a log–linear relationship with healing time, with wet samples showing higher recovery rates than dry samples. Based on experimental observations, the following assumptions are applied to both conditions.

First, for dry samples after healing, the tensile strength $\chi_0(t)$, and cohesion $C_0(t)$ remain constant at 10 Pa and 20 Pa, respectively, matching the non-healed state. This is supported by the observation that compacted samples lack cohesion even after 192 days of healing. In contrast, the initial friction coefficient ($\tan \phi_0(t)$) increases with healing time according to

$$\tan \phi_0(t) = H(t) \cdot \tan \phi_0, \quad H(t) = 0.34 \ln(t) + 0.19 \quad (5.27)$$

Based on Eq. (5.26), the mechanical properties and fracture energy increase with healing time, as shown in Table 5.1, and Figure 5.12 (a) illustrates the corresponding expansion of the yield surface for dry samples, resulting from the increase in mechanical properties after healing as listed in Table 5.1. At $t = 42$ days, $H(t) = 1.46$ and the initial friction coefficient ($\tan \phi_0(t)$) increases to 0.417 from the initial value of $\tan \phi_0 = 0.285$. The residual friction coefficient is taken as 0.304, based on experimental results (friction angle is 16.9°), giving a peak shear stress of 22.7 kPa at a normal stress of 54.4 kPa. For t

= 192 days, $H(t) = 1.98$, and the initial friction coefficient ($\tan \phi_0(t)$) increases to 0.565, and the corresponding peak shear stress at the same normal stress is 30.8 kPa. These predictions are close to the experimental peak shear stresses of 22.3 kPa (D-T042) and 31.0 kPa (D-T192).

Second, for wet samples, the initial friction coefficient is assumed to remain the same as in the non-healed sample (W-T000), at 0.9. After healing, both $\chi_0(t)$ and $C_0(t)$ increase proportionally with $H(t)$, maintaining a constant ratio $C_0(t)/\chi_0(t) = 5$, as shown in Eq. (5.28).

$$\chi_0(t) = H(t) \cdot \chi_0, \quad C_0(t) = H(t) \cdot C_0, \quad H(t) = 41.2 \ln(t) + 5.61 \quad (5.28)$$

As shown in Table 5.1 and Figure 5.12 (b), for a sample healed for 17 days, $H(t) = 1.15$. Taking the non-healed values $\chi_0 = 300$ Pa and $C_0 = 1500$ Pa, the healed sample with 42 days has $\chi_0(t) = 47.9$ kPa and $C_0(t) = 239.3$ kPa for the interface element, with $\tan \phi_0(t)$ unchanged at 0.9. Under these conditions, the peak shear stress is 212 kPa at a normal stress of 54.4 kPa, which is close to the experimental values for W-T042-A (211.3 kPa) and W-T042-B (204.8 kPa). After 373 days of wet healing, $\chi_0(t)$ and $C_0(t)$ increase to 74.9 kPa and 374.2 kPa, giving a peak shear stress of 292.9 kPa at the same normal stress.

Table 5.1 Parameters of interface elements for different healing times.

Healing time	Healing factor ($H(t)$)	Tensile strength $\chi_0(t)$, (Pa)	Cohesion $C_0(t)$ (Pa)	Initial friction coefficient ($\tan \phi_0(t)$)	Residual friction coefficient ($\tan \phi_r$)	Fracture energy ($G_f^I(t)$ $G_f^{II}(t)$) (N/m)
Dry samples						
0	--	10	20	0.285	0.095 – 0.266	0.00200
17	1.15	10	20	0.329	0.114 – 0.259	0.00231
42	1.46	10	20	0.417	0.205 – 0.388	0.00293
115	1.81	10	20	0.515	0.162 – 0.431	0.00362
192	1.98	10	20	0.565	0.119 – 0.516	0.00398
Wet samples						
0	--	300	1500	0.9	0 – 0.885	0.20
3	51	15258	76290	0.9	0 – 0.848	10.2
8	91	27378	136891	0.9	0 – 0.894	18.3
17	122	36692	183463	0.9	0 – 0.854	24.5
42	160	47869	239344	0.9	0 – 0.839	31.9
115	201	60316	301578	0.9	0 – 0.942	40.2
373	250	74855	374277	0.9	-	49.9

Note: The residual friction coefficients are taken from the experimental results in Table 3.1 of Chapter 3.

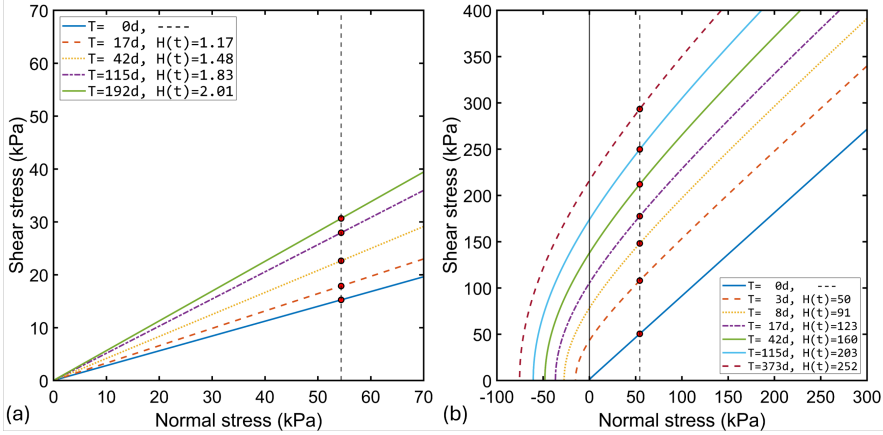


Figure 5.12 The expansion of the yield surface with healing time under dry and wet conditions is shown in panels (a) and (b), respectively, illustrating only the first and second quadrants. The dashed line parallel to the Y-axis indicates a compressive stress of 54.4 kPa, and the red dots mark the corresponding shear stresses at this normal stress. For the dry samples, the shear stresses are 17.9, 22.7, 28.1, and 30.8 kPa at healing times of 0, 17, 42, 115, and 192 days, respectively. For the wet samples, the peak shear stresses are 50.1, 108.0, 148.1, 177.7, 212.0, 249.8, and 293.3 kPa at healing times of 0, 3, 8, 17, 42, 115, and 373 days, respectively.

For the numerical simulations of healed samples, the same geometry and boundary conditions are employed (Figure 5.7). The values for mechanical parameters and fracture energy of interface elements are shown from Table 5.1.

For the dry samples, the numerical and experimental shear stress–displacement responses after healing times of 17, 42, 115, and 192 days are shown in Figure 5.13. The peak shear stresses from the simulations agree well with the experimental data. For example, the experimental peak shear stress of D-T017 is 18.2 kPa, while the simulation yields 17.9 kPa, consistent with the analytical prediction (Figure 5.13 (a)). After 192 days of dry healing, the peak shear stresses from simulation and experiment are 30.8 kPa and 31.0 kPa, respectively (Figure 5.13 (d)). For the residual shear stress, the simulations cover the fluctuations associated with stick–slip events in D-T017, D-T115, and D-T192. In D-T042, the simulated residual stresses are 11.2 kPa (case B) and 21.1 kPa (case A), consistent with the low (0.205) and high (0.388) residual friction coefficients under a normal stress of 54.4 kPa.

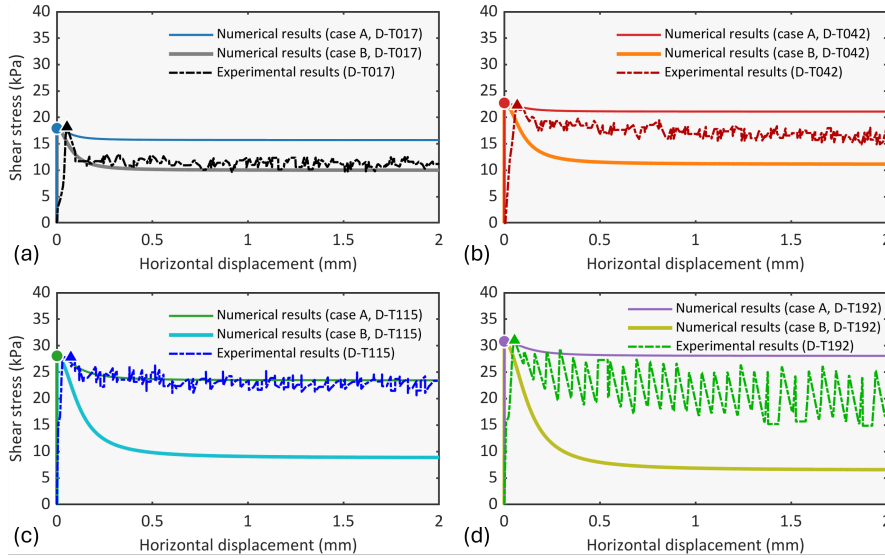


Figure 5.13. (a)–(d) present shear stress–displacement curves for dry samples D-T017, D-T042, D-T115, and D-T192. Numerical simulations (solid lines) are compared with experimental measurements (dashed lines). Triangles mark the experimental peak shear stresses, while circles indicate the numerical peaks. The numerical results (case A and case B) use high and low residual friction coefficients, respectively

For the wet samples, the numerical and experimental shear stress–displacement responses after healing times of 3, 17, 42, and 115 days are presented in Figure 5.14. The peak shear stresses from the simulations are generally consistent with the experimental data, although some variability of peak shear stress is observed between duplicated experiments. For example, in W-T017 the simulation result shows a peak shear stress of 177.7 kPa, which falls within the experimental range (108.0 kPa for W-T042-A and 215.0 kPa for W-T042-B). For the 42-day wet-healed sample, the two experimental repeats show slightly different peak values (211.3 kPa for W-T042-A and 204.8 kPa for W-T042-B), while the numerical result (212.0 kPa) is in close agreement with the experimental values. It should also be noted that in the simulations, the stress buildup occurs rapidly due to the high stiffness assigned to the interface elements (1E5 MPa/m), whereas in the experimental wet samples, the stress increases more gradually, typically over the first 1 mm of horizontal displacement.

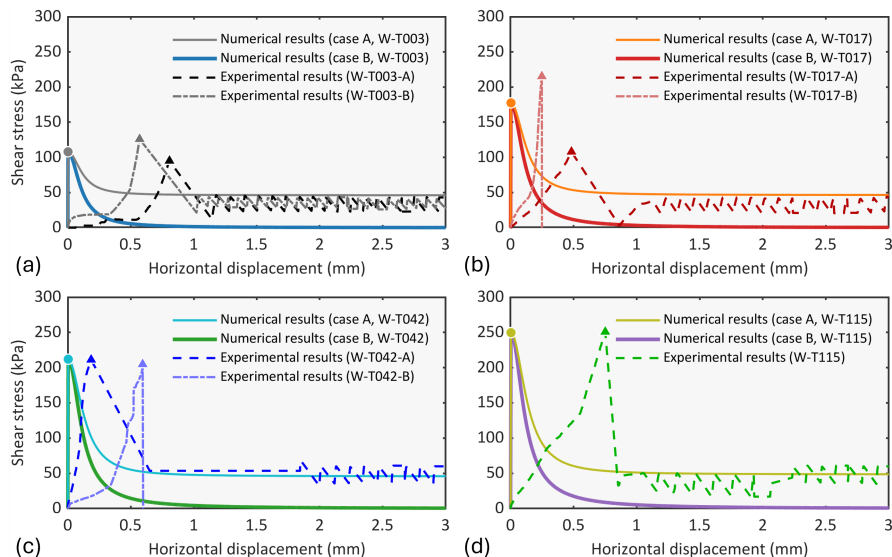


Figure 5.14 (a)–(d) show the shear stress–displacement curves for wet samples after 3, 17, 42, and 115 days of healing. Numerical simulations (solid lines) are compared with experimental measurements (dashed lines). Triangles denote the experimental peak shear stresses, while circles indicate the numerical peaks.

The relationship between peak shear stress and healing time under dry and wet conditions is shown in Figure 5.15. Numerical results (red circles) and experimental data (blue triangles) exhibit a clear log-linear trend, highlighted by the fitted line. The close agreement demonstrates that the model captures the healing behaviour in both dry and wet samples.

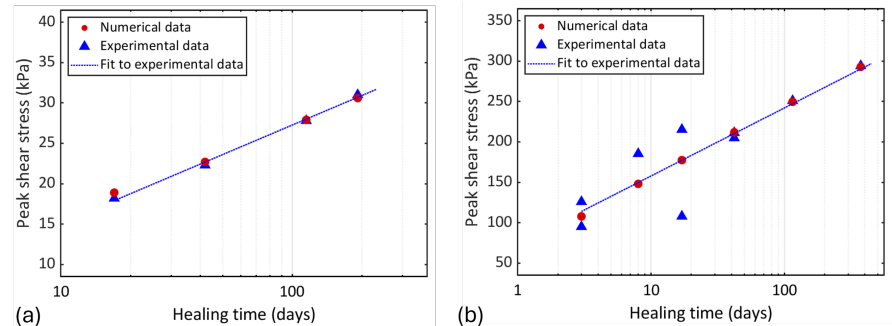


Figure 5.15 Peak shear stress versus healing time with numerical results (red circles), experimental data (blue triangles), and fitted lines: (a) dry conditions; (b) wet conditions.

5.2.4.2 Extended healing time.

Now that we have shown this model can reasonably fit the experimental data for healing times between 0 and 373 days, we can extend it to consider long-term healing over 1, 10, and 20 years, given that the typical operational lifetime of a rock salt cavern is about 20–50 years (Bai et al., 2025). As shown in Figure 5.16, under a normal stress of 55.4 kPa, the peak shear strength for dry samples increases from 34.21 kPa at 1 year to 46.39 kPa at 10 years, after which it slows and only increases to 50.12 kPa at 20 years. Wet samples show a larger increase. The peaks rise from 292.08 to 376.16 kPa over the first 10 years, and to 401.31 kPa by 20 years. This continuing but slowing recovery aligns with the micro mechanisms identified in the direct shear tests. In dry conditions, as discussed in Chapters 3 and 4, we interpreted healing to be governed by plastic deformation through dislocation-driven recovery and limited contact-level rearrangement, which gradually reduces defect density but results in only modest asperity welding and minimal aperture reduction. As defect density decreases and stresses are progressively relaxed, the driving force for further recovery becomes weaker, so that the recovery rate slows over time. In wet conditions, as discussed in Chapters 3 and 4, we interpreted healing to occur through crystallization. This process smooths stressed contacts and forms precipitated bridges that increase the effective contact area, thereby reducing stress on the asperities. Because the deformation mechanisms are stress-driven, further strengthening proceeds only incrementally (Houben et al., 2013).

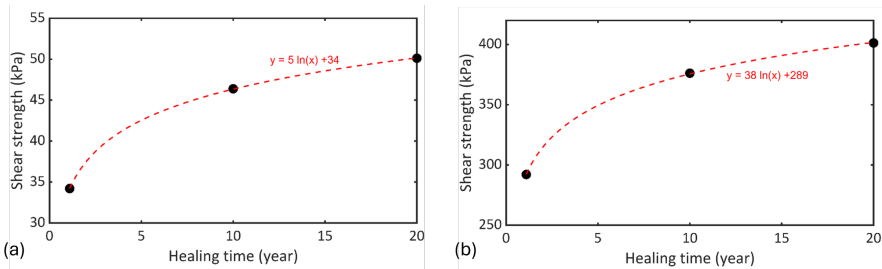


Figure 5.16 Shear strength (i.e., peak shear stress) of healed samples after 1, 10, and 20 years under (a) dry and (b) wet conditions.

5.3 Conclusions

This study uses an existing zero-thickness cohesive constitutive model within an elasto-plastic framework (Caballero et al. 2008) with an incorporated expression for time-dependent healing. The model is compared to simulations of healed dry and wet samples, as well as extended healing time scenarios. The main points are:

(1) The existing model reproduces the mechanical response of the experiments of Chapter 3, i.e. the full experimental shear stress response across all five loading stages, including the peak shear stress and the transition to the residual shear stress. The stick-slip behaviour (stress fluctuations) observed in the experiments is not reproduced in the numerical simulations, but this is considered beyond the scope of this chapter.

(2) We introduce the time-dependent healing effect as a healing factor (external variable) governed by a log-linear relationship with healing time. The increase in mechanical properties during healing enables expansion of the yield surface, including fracture energy. Based on experimental observations, assumptions are also defined for both dry and wet healed samples.

(3) The model reproduces the peak shear stress and residual state of each healed sample and incorporates a log-linear dependence on healing time, which is then used to extend the simulation to longer healing periods. Assuming the numerical model accurately captures the relevant physical processes, the extended healing time simulations show that after 1, 10 and 20 years, shear strength continues to recover; however, with reduced rates after 20 years. This suggests that the samples will not fully regain their original strength under a normal stress of 55.4 kPa.

5.4 References

- Alfano, G., & Sacco, E. 2006. Combining interface damage and friction in a cohesive-zone model. *International Journal for Numerical Methods in Engineering*, 68(5), 542–582. <https://doi.org/10.1002/nme.1728>
- Alsheghri, A. A., & Abu Al-Rub, R. K. 2016. Finite element implementation and application of a cohesive zone damage-healing model for self-healing materials. *Engineering Fracture Mechanics*, 163, 1–22. <https://doi.org/10.1016/j.engfracmech.2016.06.010>
- Alsheghri, A.A. and Al-Rub, R.K.A., 2015. Thermodynamic-based cohesive zone healing model for self-healing materials. *Mechanics Research Communications*, 70, pp.102–113. <https://doi.org/10.1016/j.mechrescom.2015.10.003>
- Bai, W., Shi, X., Zhu, S., Wei, X. and Huang, Y., 2025. Opportunities and challenges of large-scale salt cavern hydrogen storage in China coupled with renewable energy sources. *Clean Energy*, 9(1), pp.179–196. <https://doi.org/10.1093/ce/zkae095>
- Barenblatt, G.I., 1962. The mathematical theory of equilibrium cracks in brittle fracture. *Advances in applied mechanics*, 7, pp.55–129. [https://doi.org/10.1016/S0065-2156\(08\)70121-2](https://doi.org/10.1016/S0065-2156(08)70121-2)
- Bérest, P., Brouard, B. and Durup, J.G., 2001. Tightness tests in salt-cavern wells. *Oil & Gas Science and Technology*, 56(5), pp.451–469. <https://doi.org/10.2516/ogst.2001037>
- Bland, D.R., 1957. The associated flow rule of plasticity. *Journal of the Mechanics and Physics of Solids*, 6(1), pp.71–78. [https://doi.org/10.1016/0022-5096\(57\)90049-2](https://doi.org/10.1016/0022-5096(57)90049-2)
- Caballero, A., Willam, K. J., & Carol, I. 2008. Consistent tangent formulation for 3D interface modeling of cracking/fracture in quasi-brittle materials. *Computer Methods in Applied Mechanics and Engineering*, 197(33–40), 2804–2822. <https://doi.org/10.1016/j.cma.2008.01.011>
- Carol, I., López, C.M. and Roa, O., 2001. Micromechanical analysis of quasi-brittle materials using fracture-based interface elements. *International Journal for Numerical Methods in Engineering*, 52(1–2), pp.193–215. <https://doi.org/10.1002/nme.277>
- Cendón, D.A., Gálvez, J.C., Elices, M. and Planas, J., 2000. Modelling the fracture of concrete under mixed loading. *International journal of fracture*, 103(3), pp.293–310. <https://doi.org/10.1023/A:1007687025575>
- Cerfontaine, B., Dieudonné, A. C., Radu, J. P., Collin, F., & Charlier, R. (2015). 3D zero-thickness coupled interface finite element: Formulation and application. *Computers and Geotechnics*, 69, 124–140. <https://doi.org/10.1016/j.compgeo.2015.04.016>
- Chen, Z., Bungler, A. P., Zhang, X., & Jeffrey, R. G. 2009. Cohesive zone finite element-based modeling of hydraulic fractures. *Acta Mechanica Solida Sinica*, 22(5), 443–452. [https://doi.org/10.1016/S0894-9166\(09\)60295-0](https://doi.org/10.1016/S0894-9166(09)60295-0)
- Dugdale, D.S., 1960. Yielding of steel sheets containing slits. *Journal of the Mechanics and Physics of Solids*, 8(2), pp.100–104. [https://doi.org/10.1016/0022-5096\(60\)90013-2](https://doi.org/10.1016/0022-5096(60)90013-2)
- Elices, M.G.G.V., Guinea, G.V., Gomez, J. and Planas, J., 2002. The cohesive zone model: advantages, limitations and challenges. *Engineering fracture mechanics*, 69(2), pp.137–163. [https://doi.org/10.1016/S0013-7944\(01\)00083-2](https://doi.org/10.1016/S0013-7944(01)00083-2)
- Freeman, B. and Jefferson, A., 2024, May. A 3D coupled finite element model for self-healing quasi-brittle materials. In *Engineering Research Conference 2023* (p. 29). doi.org/10.18573/conf1.c
- Gao, W., Liu, X., Hu, J. and Feng, Y.T., 2022. A novel bilinear constitutive law for cohesive elements to model the fracture of pressure-dependent rocks. *Rock Mechanics and Rock Engineering*, 55(2), pp.521–540. <https://doi.org/10.1007/s00603-021-02671-0>
- Garagash, D. I. 2019. Cohesive-zone effects in hydraulic fracture propagation. *Journal of the Mechanics and Physics of Solids*, 133. <https://doi.org/10.1016/j.jmps.2019.103727>
- Garolera, D., Carol, I. and Papanastasiou, P., 2020. Application of zero-thickness interface elements to sanding prediction analysis. *Journal of Petroleum Science and Engineering*, 190, p.107052. <https://doi.org/10.1016/j.petrol.2020.107052>
- Goodman, R.E., Taylor, R.L. and Brekke, T.L., 1968. A model for the mechanics of jointed rock. *Journal of the soil mechanics and foundations division*, 94(3), pp.637–659. <https://doi.org/10.1061/JSEAQ.0001133>
- Grgic, D., Al Sahyouni, F., Golfier, F., Moumni, M. and Schoumacker, L., 2022. Evolution of gas permeability of rock salt under different loading conditions and implications on the underground hydrogen storage in salt caverns. *Rock Mechanics and Rock Engineering*, 55(2), pp.691–714. <https://doi.org/10.1007/s00603-021-02681-y>
- Groenenberg, R., Koornnef, J., Sijm, J., Janssen, G., Morales-Espana, G., Van Stralen, J., Hernandez-Serna, R., Smekens, K., Juez-Larre, J., Goncalvez, G. and Wasch, L.J., 2020. Large-scale energy storage in salt caverns and depleted fields (Ises)—project findings. *TNO* 2020 R12006
- Houben, M. E., ten Hove, A., Peach, C. J., & Spiers, C. J. 2013. Crack healing in rocksalt via diffusion in adsorbed aqueous films: Microphysical modelling versus experiments. *Physics and Chemistry of the Earth*, 64, 95–104. <https://doi.org/10.1016/j.pce.2012.10.001>
- Leigh, C.D. and Hansen, F.D., 2011. Salt disposal of heat-generating nuclear waste (No. SAND2011-0161). Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States). <https://doi.org/10.2172/1005078>
- Li, Z., Kang, Y., Fan, J., Fourmeau, M., Chen, J., Jiang, D. and Nelias, D., 2024. Macroscopic experimental study and microscopic phenomenon analysis of damage self-healing in salt rock. *Engineering Geology*, 338, p.107634. <https://doi.org/10.1016/j.enggeo.2024.107634>
- Liang, W.G., Yang, C.H., Zhao, Y.S., Dusseault, M.B. and Liu, J., 2007. Experimental investigation of mechanical properties of bedded salt rock. *International Journal of Rock Mechanics and Mining Sciences*, 44(3), pp.400–411. <https://doi.org/10.1016/j.ijrmms.2006.09.007>
- Liaudat, J., Dieudonné, A.C., and Vardon P.J., 2023. Modelling gas fracturing in saturated clay samples using triple-node zero-thickness interface elements. *Computers and Geotechnics* 154, pp. 105128. <https://doi.org/10.1016/j.compgeo.2022.105128>
- Liu, W., Li, Q., Yang, C., Shi, X., Wan, J., Jurado, M.J., Li, Y., Jiang, D., Chen, J., Qiao, W. and Zhang, X., 2023. The role of underground salt caverns for large-scale energy storage: A review and prospects. *Energy Storage Materials*, 63, p.103045. <https://doi.org/10.1016/j.ensm.2023.103045>
- Martínez, A., Liaudat, J., López, C. M., & Carol, I. 2023. 3D zero-thickness interface model for fracture of cement-based materials with chemical degradation. *International Journal of Solids and Structures*, 238. <https://doi.org/10.1016/j.ijsolstr.2021.111379>
- Nie, Y., Sheikh, A., Griffith, M. and Visintin, P., 2022. A damage-plasticity based interface model for simulating in-plane/out-of-plane response of masonry structural panels. *Computers & Structures*, 260, p.106721. <https://doi.org/10.1016/j.compstruc.2021.106721>
- Ponnusami, S. A., Krishnasamy, J., Turteltaub, S., & van der Zwaag, S. 2018. A cohesive-zone crack healing model for self-healing materials. *International Journal of Solids and Structures*, 134, 249–263. <https://doi.org/10.1016/j.ijsolstr.2017.11.004>

- Ruiz, G., Pandolfi, A. and Ortiz, M., 2001. Three-dimensional cohesive modeling of dynamic mixed-mode fracture. *International Journal for Numerical Methods in Engineering*, 52(1-2), pp.97-120. <https://doi.org/10.1002/nme.273>
- Salzer, K., Popp, T., & Böhnel, H., 2017. Mechanical and permeability properties of highly pre-compacted granular-salt bricks. In *The Mechanical Behavior of Salt – Understanding of THMC Processes in Salt* (pp. 239–248).
- Schimmel, E.C. and Remmers, J.J.C., 2006. Development of a constitutive model for self-healing materials. *Delft Aerospace Computational Science*.
- Siemann, L., Leuger, B. and Zapf, D., 2019, January. Temperature induced and gas-pressure driven fractures in rock salt: Insights from numerical calculations and laboratory measurements. In *Geophysical Research Abstracts* (Vol. 21).
- Taleghani, A.D., Gonzalez-Chavez, M., Yu, H. and Asala, H., 2018. Numerical simulation of hydraulic fracture propagation in naturally fractured formations using the cohesive zone model. *Journal of Petroleum Science and Engineering*, 165, pp.42-57. <https://doi.org/10.1016/j.petrol.2018.01.063>
- Volokh, K.Y., 2004. Comparison between cohesive zone models. *Communications in Numerical Methods in Engineering*, 20(11), pp.845-856. <https://doi.org/10.1002/cnm.717>
- Zou, Z., & Hameed, M. 2018. Combining interface damage and friction in cohesive interface models using an energy based approach. *Composites Part A: Applied Science and Manufacturing*, 112, 290–298. <https://doi.org/10.1016/j.compositesa.2018.06.017>

6. Conclusions and recommendations

This thesis investigates how fluid–rock interactions affect the evolution of fracture geometry and mechanical properties in rock salt. A custom-designed flow-through experimental setup with visualization capabilities is developed to study the dissolution behaviour of rock salt fractures, while shear box tests are conducted to assess mechanical recovery, and fracture surface microstructure is recorded using microscopy. These experiments are complemented by numerical simulations that replicate laboratory conditions and extend the analysis to temporal scales under varying loading scenarios. Together, these methods provide an integrated understanding of fracture evolution in rock salt. The following section summarizes the conclusions and discusses their implications for salt cavern performance in energy storage and radioactive waste disposal, and provides suggestions for future research.

6.1 Conclusions

6.1.1 Dissolution of rock salt fractures

Our combined experimental and numerical results show that the dissolution of rock salt fractures is not uniform, but instead heterogeneous and shaped by both fluid flow and concentration conditions and initial geometry (Chapter 2). In the experiments, dissolution consistently localizes at fracture inlets and sharp corners, gradually smoothing the surfaces and reducing roughness as flow progresses. This smoothing has two consequences: it lowers the geometrical control on dissolution over time, and it modifies flow pathways such that the dominant controls on dissolution shift from surface area effects toward flow-driven processes.

Fractures with larger initial surface areas dissolve faster and lose more mass, confirming the role of geometry in governing early-stage dissolution. A larger surface area is often tied to greater surface roughness, which increases reactive sites and enhances dissolution. However, this influence diminishes at higher flow rates and concentrations, where hydrodynamic conditions exert stronger control. In practice, this indicates that dissolution behaviour is scale- and regime-dependent: geometric effects dominate under low-flow, low-concentration conditions, while advective transport dominates when flow is intensified.

Another outcome is that dissolution patterns observed at the centimeter scale deviate from classical predictions based on Péclet–Damköhler frameworks, which are commonly applied to pore- and microscale fractures. The heterogeneous dissolution fronts, evolving surface roughness, and scale-dependent effects highlight the limitations of applying such scaling directly to larger fracture systems. Our experiments provide visual confirmation that widely used numerical simulation programs, such as COMSOL, adequately capture key solute transport features, including near-saturation zones at fracture boundaries and convex velocity–concentration profiles, confirming the coupling between fracture geometry and transport processes. At the same time, by revealing the consistently asymmetric evolution of geometry during dissolution, these findings

simultaneously emphasize that fracture permeability in rock salt does evolve in a complex manner, emerging from the interplay between evolving fracture geometry, flow conditions, and solute gradients.

6.1.2 Healing of fractures in rock salt

Our direct shear experiments of healed samples show that fracture healing in rock salt is a time dependent process that can substantially restore shear strength, but the efficiency is strongly controlled by environmental conditions and fracture surface roughness (Chapters 3 and 4). Healing follows a log-linear trend with time, with brine accelerating recovery by up to seven times compared to dry conditions; although each data point represents an independent measurement at a specific healing duration, we interpret them collectively as indicative of a continuous healing process. Our mechanical and microstructural results combined suggest that the fluid assisted processes of pressure solution, recrystallization, and surface energy minimization play a central role in enhancing mechanical recovery, whereas in the absence of fluids healing is limited to slower dislocation driven plastic flow.

Additionally, healing alters both mechanical properties and surface topography. The residual friction angle evolves differently under dry and wet conditions: it increases over time in dry fractures but remains constant in wet fractures, although wet fractures maintain consistently higher values. Surface analyses confirm that healing modifies fracture morphology, producing rougher interfaces and altering the sliding behaviour. Stick-slip instabilities occur in all samples, but with markedly different characteristics: dry fractures display frequent small stress drops, whereas wet fractures show less frequent but larger events. These contrasting behaviours suggest that the controlling mechanisms shift from distance dependent frictional instabilities in dry conditions to velocity dependent processes in the brine. Another outcome is the role of initial fracture roughness. Healing is more efficient when opposing surfaces are relatively smooth, while rougher fractures show limited recovery. This suggests that aperture size is a critical factor, as larger openings hinder crystal growth across the fracture and reduce the formation of effective mechanical bridges.

6.1.3 Long-term strength recovery of rock salt fractures.

We performed a numerical study that shows how fracture strength recovery in rock salt can be represented by incorporating healing within an existing elasto-plastic constitutive framework. By incorporating a time dependent recovery of tensile strength, cohesion, and friction coefficient, the cohesive zone model presented in Chapter 5 extends existing elasto-plastic formulations, reproduces experimental behaviour, and establishes healing as a process that can be included in long-term predictions.

This approach demonstrates that the healing process under laboratory conditions does not progress linearly. Instead, recovery follows a logarithmic trend over extended timescales, with rapid strengthening during the early stages and progressively slower changes thereafter. Over periods of years to decades, the effect of time on further strength increase becomes negligible under a normal stress of 55.4 kPa. These results

suggest that, although fractures can regain a significant portion of their strength, complete recovery to the state of intact rock is unlikely under this stress condition. Consistent with the experimental observations, the simulations indicate that healing is strongly influenced by the presence of fluid, with wet environments accelerating the healing process.

6.1.4 Implications for salt caverns

The lifetime of a salt cavern, from its creation through operation to eventual abandonment, typically spans several decades. The following sections discuss how the findings of this study can be applied to the different phases of a cavern's life cycle.

Leaching: During leaching, the upper part of the cavern (i.e., the cavern roof) is protected by a blanket medium such as oil or nitrogen, while the lower part is exposed to undersaturated solutions (Buzogany et al., 2024). In this lower region, fractures can develop around the cavern wall and progressively enlarge through dissolution. Our results indicate that dissolution preferentially removes material near the cavern wall and along fracture edges, leading to increased fracture aperture and enhanced permeability within the damage zone. In areas with pre-existing fractures, those with larger reactive surface areas tend to dissolve more rapidly. As fractures grow and become interconnected, the total reactive surface increases, accelerating mass loss and potentially threatening the long-term integrity of the salt cavern. Following the results of Chapter 2, which showed that dissolution mass decreases as fluid flow rate increases, this work suggests that higher flow rates are preferable, as they reduce the overall dissolution rate by shortening the contact time between the fluid and fracture surfaces, thereby limiting the enlargement of rock salt fractures. Additionally, fracture surfaces tend to evolve toward smoother profiles, particularly under low flow rates and low salt concentrations, where prolonged fluid–rock interaction gradually reduces surface roughness. For simulation purposes, COMSOL Multiphysics is well suited to resolve fracture flow, brine undersaturation, and dissolution-controlled wall retreat using level set or moving boundary formulations (see Chapter 2). Such models capture the coupled feedback among aperture growth, velocity, and mass transfer, governed by reaction kinetics and transport, but they do not account for the evolution of surface roughness revealed by the dissolution experiments.

Storage cycles: During storage, the lower part of a rock salt cavern remains in contact with saturated brine, whereas the upper part is exposed to the stored material. During injection and withdrawal, the brine interface moves vertically, so the upper and lower regions experience relatively dry and wet conditions, respectively. Experiments in Chapter 3 show a log-linear recovery of shear strength, with the fastest increase within the first month. Under dry conditions, shear strength approximately doubles within six months, while saturated brine accelerates recovery, with fractures in the damage zone regaining up to six times their initial strength within one year. Stress effects are important when interpreting these results for caverns. The applied normal stress in our experiments is much lower than in-situ stress, and higher confining pressure is known to enhance healing. For dry samples, tests at radial pressures of 3, 7, 14, and 20 MPa show a linear relationship between healing and confining pressure (Fuenkajorn et al., 2011), suggesting

that recovery under in-situ conditions may be faster while retaining the log-linear time dependence. These findings have implications for operational timing, including gas or fluid injection and brine displacement. Gas storage caverns typically follow annual injection–withdrawal cycles, often supplemented by shorter term adjustments (Groenenberg et al., 2020; Kumar et al., 2023; Li et al., 2024). Since a substantial fraction of recovery occurs within about one month under both dry and wet conditions, cycling intervals longer than one month would allow meaningful healing between phases, supporting long-term stability. However, extrapolation to the field remains uncertain because laboratory stresses are lower and imposed shear rates are higher than geological conditions, and healing under representative stresses and deformation rates requires further quantification.

Abandonment: During the abandonment phase, when the cavern is fully saturated, long-term healing can promote fracture closure and mechanical recovery within the damaged zone. As shown in Chapter 4, rough fracture surfaces initially exhibit larger apertures, which hinder the formation of load bearing bridges between opposing faces and therefore limit early strength recovery. Nevertheless, the measured increase in shear strength indicates enhanced fracture resistance and improved rock mass integrity, even where initial damage is minor. Over years to decades, recovery is expected to continue, but with a progressively decreasing rate. In addition to healing, rock salt undergoes creep under sustained in-situ stress. When pressure cycling ceases, the surrounding rock salt is no longer subjected to cyclic loading, and steady state creep can become the dominant deformation mechanism. This creep driven deformation can promote fracture closure and strength recovery independently of healing. This mechanism is particularly relevant for abandoned caverns, where long-term creep contributes to mechanical stabilisation of the surrounding rock mass. However, creep induced cavern convergence also reduces cavern volume and may increase internal pressure, which could elevate the risk of fracture initiation at the cavern wall if pressure builds toward in-situ stress (Bérest et al., 2001).

6.2 Recommendations for future research

6.2.1 Improving visualization of fracture evolution

This thesis monitors fracture geometry primarily through camera-based imaging, which yields 2D projections of processes occurring in three dimensions. Additionally, CT scans capture the sample geometry before and after the experiments. This limits the ability to capture changes in aperture distribution, connectivity, and dissolution patterns within the fracture volume. 3D imaging techniques such as X ray microtomography and computed tomography (e.g., Gouze et al., 2003; Weisbrod et al., 2012) could provide a more complete representation of fracture morphology and allow quantification of dissolved mass through volumetric analysis of the remaining rock. Compared to 2D methods, these techniques offer higher spatial resolution and enable the reconstruction of evolving structures, which can be linked more directly to permeability changes and flow pathways across space and time. There are, however, also challenges. High resolution CT scanning requires careful sample preparation in case of any fluid leakage,

which poses risks to both equipment and data quality. Time resolved 3D imaging is further constrained by scanning duration and cost.

6.2.2 Investigating fracture roughness effect in dissolution

To investigate the physical properties of fractures, we employed three simplified rectangular rock salt channels (i.e., 2.5D) to study dissolution and transport processes and to derive the evolution laws of fracture geometry and permeability. While Zhou et al. (2022) developed soluble microfluidic chips with rough channels, their system was limited to a 2D representation and did not capture fracture depth. In contrast, natural fracture surfaces are significantly more complex (Deng et al., 2019), and accurately replicating their morphology remains a major challenge. Future research should investigate how more realistic and complex roughness patterns influence dissolution behaviour at the decimetre scale in 3D space. Using the Snapmaker 350 (resolution 0.1 mm, as described in Chapter 2), it is possible to fabricate fractures with wavy or sawtooth longitudinal profiles featuring varying JRC roughness, rather than using a simplified rectangular geometry (Scesi et al., 2007). Alternatively, natural fracture surfaces can be scanned with a digital microscope (as described in Chapters 3 and 4); the resulting stitched 3D profiles can then be processed using Python or MATLAB and exported to the Snapmaker 350 to produce accurate replicas.

6.2.3 Exploring sealing behaviour of rock salt fractures under stress

Regarding fracture permeability evolution due to dissolution/precipitation processes, no significant changes were observed in this study. This is likely due to the absence of precipitation and the relatively large initial fracture apertures. Dissolution was the dominant process, even at a flow rate of 2 mL/min and a salt concentration of 300 g/L. In contrast, sealing behaviour (i.e., fracture aperture and permeability reduction) has been reported by Elkhoury et al. (2015), who conducted reactive flow experiments on fractured dolomitic anhydrite cores. Using an optical profilometer, they visualized fracture geometry changes under confining stress (7 MPa) and at lower flow rates ranging from 0.01 to 0.6 mL/min. Additionally, the permeability of naturally fractured carbonate core samples was tested under varying confining stresses during fluid flow. The results revealed a linear relationship between the cube root of permeability and the logarithm of confining pressure (i.e., permeability reduction as confining pressure increasing) (Jones et al., 1975). To evaluate the potential for sealing in rock salt fractures over the lifespan of a salt cavern, future experiments should incorporate lower flow rates and apply normal stress to the fracture surfaces to more accurately simulate in-situ conditions. Under these conditions, advanced visualization techniques such as CT scanning mentioned above would be essential for capturing the evolution of fracture geometry. The advantage of this approach is that it would provide insight into fracture behaviour under conditions comparable to those in-situ, where both mechanical closure and chemical processes may influence long-term evolution of rock salt fracture geometry. At the same time, the added complexity of stress loading and the use of very low flow rates would require longer measurement times, and careful management of fluid leakage risks.

6.2.4 Recovery of the tensile strength upon healing

In terms of mechanical evolution of rock salt fractures, we focus on the shear strength recovery and associated friction behaviour. Considering that fractures in the damage zone might be both shear and tension fractures, future research is recommended to investigate the tensile strength recovery of the salt fractures upon healing (Li et al., 2024). Such studies could focus on the evolution of tensile strength during the healing process, utilizing methods such as the Brazilian Splitting Test or the Three-Point Bending Test. Although not addressed here, shear and tensile strength of rock fractures are known to be positively correlated (Jaeger et al., 2009). Recovery of tensile strength differs from that of shear strength. Closure across the fracture aperture is primarily driven by the formation of new bonds, which enhance cohesion and contribute to both tensile and shear recovery. However, tensile healing is assumed to be dominated by bond formation, whereas shear recovery is additionally influenced by frictional resistance associated with surface roughness. Investigating tensile healing in parallel with shear behavior would provide a more comprehensive understanding of fracture evolution in rock salt and improve predictions of long-term cavern stability.

6.2.5 Healing under open system conditions with normal stress

This study investigates fracture healing in closed, static, saturated brine environments using wet samples. While such conditions provide insight into the intrinsic healing capacity of rock salt, they do not fully represent the operational setting of salt caverns. In practice, caverns are subject to cyclic injection and withdrawal of storage materials, during which brine is in motion. Under these circumstances, fractures are exposed not only to fluid flow but also to normal stress, and healing may occur simultaneously with mass transfer.

Future work about rock salt fracture healing should therefore focus on open systems that incorporate sustained fluid flow and applied stress. Continuous monitoring of permeability during such experiments, combined with post-healing strength measurements, would allow a more complete assessment of the coupled evolution of hydraulic and mechanical properties. Previous studies in other lithologies, including sandstone, clay, granite, and limestone, show that permeability and strength can evolve together under stress and flow, and that healing rates may decrease at higher flow rates (Tenthorey et al., 2003; Ishibashi et al., 2016; Zhang et al., 2017). Moreover, the effect of normal stress on fracture healing was not investigated in this study. Previous research by Fuenkajorn et al. (2011) reported a linear relationship between healing and confining pressure in dry samples. The influence of normal stress on healing rates under dry and wet conditions has been widely studied, primarily focusing on the frictional strength of granular materials acting as fault gouge to better understand seismicity (Rutter et al., 1979; Bos et al., 2002; Pluymakers, 2015). Extending flow-through healing experiments in rock salt to include applied stress would thus capture the interplay between mechanical closure, fluid flow, and chemical processes. Although such experiments are technically demanding, they would generate results directly relevant to the long-term performance and stability of salt caverns.

6.2.6 Incorporating acoustic emission monitoring in shear experiments

Another aspect of the shear box tests was the audible stick-slip occurred throughout the experiments. Stick-slip behaviour was originally proposed as an analogue for earthquake rupture by Brace and Byerlee (1966). Analysis of these events showed that, while their frequency remained constant in wet samples, the associated stress drops were three to five times greater than in dry samples. However, this interpretation is based solely on stress response. In the context of salt caverns, pressure imbalance between the stored material and the surrounding salt formation can lead to roof collapse and fracture formation during both storage and abandonment phases (Munson et al., 1998; Liu et al., 2020). To better understand the mechanical stability of salt cavern, incorporating acoustic emission (AE) monitoring into experimental setups is strongly recommended, as AE can capture real-time signals associated with fracture initiation and propagation (Zhang et al., 2015).

6.2.7 Incorporating the thermal and stress effects into interface model

The constitutive framework proposed in this thesis introduces a time dependent healing formulation for zero-thickness interface elements within an existing elasto-plastic law. However, gas storage operations in mined salt caverns, particularly the cyclic injection and withdrawal of hydrogen or compressed air, are expected to generate temperature fluctuations and varying stress conditions (Groenenberg et al., 2020; Wassing et al., 2022; Kumar et al., 2023; Blanco-Martín et al., 2018; Siemann et al., 2019). Since such changes can influence the creep behaviour of rock salt (Carter et al., 1983; Blanco-Martín et al., 2024), future modelling efforts should account for both the role of normal stress and thermal effects in healing.

At present, the constitutive law accounts for the influence of normal stress on the stress response. However, additional experimental data are required to validate how normal stress affects the healing process, particularly given that in-situ stresses are several orders of magnitude higher than those applied in our experiments. Extending the current constitutive framework with healing to incorporate additional degrees of freedom, such as temperature and fluid flow, would enhance its applicability. Implementation in simulation platforms such as SaveInCave (Honório et al., 2024), which already represent creep during cyclic storage, would enable model upscaling and application to more complex geological scenarios.

6.3 References

- Bérest, P., Bergues, J., Brouard, B., Durup, J.G. and Guerber, B., 2001a. A salt cavern abandonment test. *International Journal of Rock Mechanics and Mining Sciences*, 38(3), pp.357-368. [https://doi.org/10.1016/S1365-1609\(01\)00004-1](https://doi.org/10.1016/S1365-1609(01)00004-1)
- Blanco-Martín, L., Rouabhi, A., Billiotte, J., Hadj-Hassen, F., Tessier, B., Hévin, G., Balland, C. and Hertz, E., 2018. Experimental and numerical investigation into rapid cooling of rock salt related to high frequency cycling of storage caverns. *International Journal of Rock Mechanics and Mining Sciences*, 102, pp.120-130. <https://doi.org/10.1016/j.ijrmm.2018.01.008>
- Blanco-Martín, L., Rouabhi, A., Hadj-Hassen, F., Jaworowicz, J., Azabou, M., Hévin, G. and Labaune, P., 2024. Creep of rock salt under a large range of deviatoric stresses. *Rock Mechanics and Rock Engineering*, 57(8), pp.6105-6118. <https://doi.org/10.1007/s00603-024-03841-6>
- Bos, B.A.R.T. and Spiers, C.J., 2002. Fluid-assisted healing processes in gouge-bearing faults: Insights from experiments on a rock analogue system. *Pure and Applied Geophysics*, 159(11), pp.2537-2566. <https://doi.org/10.1007/s00024-002-8747-2>
- Brace, W. F., & Byerlee, J. D., 1966. Stick-slip as a mechanism for earthquakes. *Science*, 153(3739), 990-992. <https://doi.org/10.1126/science.153.3739.990>
- Buzogany, R. and Bernhardt, H., 2024, November. Hydrogen Storage in Salt Caverns-Current Status and Potential Future Research Topics. In *Fifth EAGE Global Energy Transition Conference & Exhibition (GET 2024)* (Vol. 2024, No. 1, pp. 1-4). European Association of Geoscientists & Engineers. <https://doi.org/10.3997/2214-4609.202421250>
- Carter, N.L. and Hansen, F.D., 1983. Creep of rocksalt. *Tectonophysics*, 92(4), pp.275-333. [https://doi.org/10.1016/0040-1951\(83\)90200-7](https://doi.org/10.1016/0040-1951(83)90200-7)
- Chan, K.S., Munson, D.E., Bodner, S.R. and Fossum, A.F., 1996. Cleavage and creep fracture of rock salt. *Acta Materialia*, 44(9), pp.3553-3565. [https://doi.org/10.1016/1359-6454\(96\)00004-3](https://doi.org/10.1016/1359-6454(96)00004-3)
- Deng, H. and Spycher, N., 2019. Modeling reactive transport processes in fractures. *Reviews in Mineralogy and Geochemistry*, 85(1), pp.49-74. <https://doi.org/10.2138/rmg.2019.85.3>
- Elkhoury, J. E., Detwiler, R. L., & Ameli, P. 2015. Can a fractured caprock self-heal? *Earth and Planetary Science Letters*, 417, 99-106. <https://doi.org/10.1016/j.epsl.2015.02.010>
- Fuenkajorn, K., & Phueakphum, D. 2011. Laboratory assessment of healing of fractures in rock salt. *Bulletin of Engineering Geology and the Environment*, 70(4), 665-672. <https://doi.org/10.1007/s10064-011-0370-y>
- Gouze, P., Noirot, C., Bruderer, C., Loggia, D. and Leprovost, R., 2003. X-ray tomography characterization of fracture surfaces during dissolution. *Geophysical Research Letters*, 30(5). <https://doi.org/10.1029/2002GL016755>
- Groenenberg, R., Koornnef, J., Sijm, J., Janssen, G., Morales-España, G., Van Stralen, J., Hernandez-Serna, R., Smekens, K., Juez-Larre, J., Goncalvez, G. and Wasch, L.J., 2020. Large-scale energy storage in salt caverns and depleted fields (lSES)-project findings. TNO 2020 R12006
- Honório HT, Hajibeygi H. Three-dimensional multi-physics simulation and sensitivity analysis of cyclic energy storage in salt caverns. *International Journal of Hydrogen Energy*. 2024 Dec 11;94:1389-405. <https://doi.org/10.1016/j.ijhydene.2024.11.081>
- Ishibashi, T., Asanuma, H., Fang, Y., Wang, C. and Elsworth, D., 2016, June. Exploring the link between permeability and strength evolution during fracture shearing. In *ARMA US Rock Mechanics/Geomechanics Symposium* (pp. ARMA-2016). ARMA.
- Jaeger, J.C., Cook, N.G. and Zimmerman, R., 2009. *Fundamentals of rock mechanics*. John Wiley & Sons.
- Jones Jr, F.O., 1975. A laboratory study of the effects of confining pressure on fracture flow and storage capacity in carbonate rocks. *Journal of Petroleum Technology*, 27(01), pp.21-27. <https://doi.org/10.2118/4569-PA>
- Kumar, K.R., Honorio, H., Chandra, D., Lesueur, M. and Hajibeygi, H., 2023. Comprehensive review of geomechanics of underground hydrogen storage in depleted reservoirs and salt caverns. *Journal of Energy Storage*, 73, p.108912. <https://doi.org/10.1016/j.est.2023.108912>
- Li, Z., Kang, Y., Fan, J., Fourmeau, M., Chen, J., Jiang, D. and Nelias, D., 2024. Macroscopic experimental study and microscopic phenomenon analysis of damage self-healing in salt rock. *Engineering Geology*, 338, p.107634. <https://doi.org/10.1016/j.enggeo.2024.107634>
- Liu, W., Zhang, Z., Fan, J., Jiang, D., Li, Z. and Chen, J., 2020. Research on gas leakage and collapse in the cavern roof of underground natural gas storage in thinly bedded salt rocks. *Journal of Energy Storage*, 31, p.101669. <https://doi.org/10.1016/j.est.2020.101669>
- Munson, D.E., Molecke, M.A. and Myers, R.E., 1998. Interior cavern conditions and salt fall potential (No. SAND-97-3191C; CONF-980421-). Sandia National Lab. (SNL-NM), Albuquerque, NM (United States). <https://doi.org/10.2172/650136>
- Pluymakers, A.M.H., 2015. Frictional and sealing behavior of simulated anhydrite fault gouge: Effects of CO₂ and implications for fault stability and caprock integrity (Doctoral dissertation, UU Dept. of Earth Sciences).
- Rutter, E.H. and White, S.H., 1979. The microstructures and rheology of fault gouges produced experimentally under wet and dry conditions at temperatures up to 400° C. *Bulletin de Mineralogie*, 102(2), pp.101-109.
- Scesi, L. and Gattinoni, P., 2007. Roughness control on hydraulic conductivity in fractured rocks. *Hydrogeology Journal*, 15, pp.201-211. <https://doi.org/10.1007/s10040-006-0076-6>
- Siemann, L., Leuger, B. and Zapf, D., 2019, January. Temperature induced and gas-pressure driven fractures in rock salt: Insights from numerical calculations and laboratory measurements. In *Geophysical Research Abstracts* (Vol. 21).
- Tenthorey, E., Cox, S.F. and Todd, H.F., 2003. Evolution of strength recovery and permeability during fluid-rock reaction in experimental fault zones. *Earth and Planetary Science Letters*, 206(1-2), pp.161-172. [https://doi.org/10.1016/S0012-821X\(02\)01082-8](https://doi.org/10.1016/S0012-821X(02)01082-8)
- Wassing, B., Groenenberg, R. and ter Heege, J., 2022. Modelling cyclic injection and withdrawal of gas for subsurface energy storage in salt caverns. In *The Mechanical Behavior of Salt X* (pp. 616-625). CRC Press.
- Weisbrod, N., Alon-Mordish, C., Konen, E., & Yechieli, Y. (2012). Dynamic dissolution of halite rock during flow of diluted saline solutions. *Geophysical Research Letters*, 39(9). <https://doi.org/10.1029/2012GL051306>
- Zhang, F., Fang, Y., Elsworth, D., Wang, C. and Yang, X., 2017. Evolution of friction and permeability in a propped fracture under shear. *Geofluids*, 2017(1), p.2063747. <https://doi.org/10.1155/2017/2063747>
- Zhang, Z., Zhang, R., Xie, H., Liu, J. and Were, P., 2015. Differences in the acoustic emission characteristics of rock salt compared with granite and marble during the damage evolution process. *Environmental Earth Sciences*, 73, pp.6987-6999. <https://doi.org/10.1007/s12665-015-4406-7>
- Zhou, C.X., Hu, R., Li, H.W., Yang, Z. and Chen, Y.F., 2022. Pore-scale visualization and quantification of dissolution in microfluidic rough channels. *Water Resources Research*, 58(11), p.e2022WR032255. <https://doi.org/10.1029/2022WR032255>

APPENDIX A

Appendix A provides supplemental data to Chapter 2.

A1: XRD and XRF Results

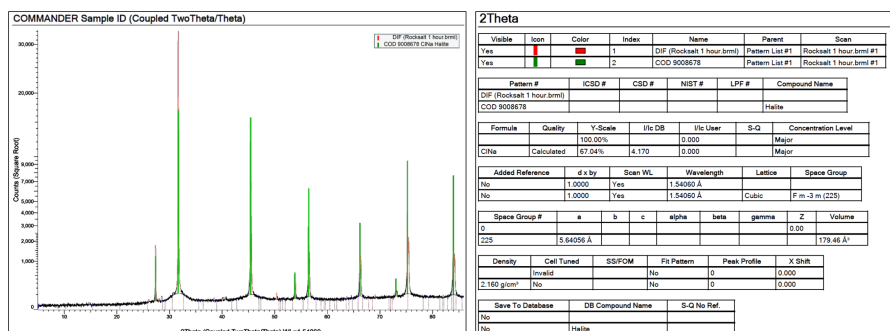


Figure A1. XRD analysis of rock salt sample.

Table A1. XRF analysis of rock salt sample.

	Element name	Concentration (wt %)
1	Cl	67.765
2	Na	31.993
3	Ca	0.065
4	K	0.049
5	Mg	0.047
6	S	0.03
7	Si	0.023
8	Fe	0.013
9	Al	0.009
10	Br	0.006

A2: Relationship between salt concentration and electrical conductivity

The relationship between electrical conductivity (EC) and sodium chloride concentration is fundamental for calculating the dissolved mass in the effluent. We calibrate the system using two saline solutions: one from the rock salt sample and one from pure sodium chloride. EC measurements across concentrations (Figure A2) show identical results, confirming the purity of rock salt is close to pure sodium chloride. Based on the equation from Rao & Thyagaraj, (2007) at 25°C, we adapt the formula for the constant experimental temperature of 20°C. The equation is shown below:

$$EC = 2.3(0.9979)^C / (C)^{0.916}$$

where C [g/L] is the salt concentration of the fluid.

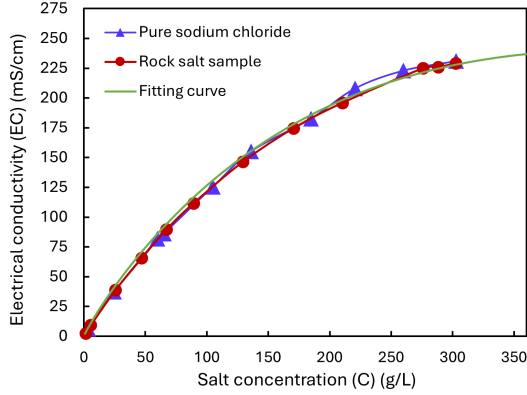


Figure A2. Electrical conductivity versus sodium chloride concentration in 20 °C.

A3: Fluid flow type

In our experiment, all injected fluid flows are classified as laminar, as confirmed by the Reynolds number calculations detailed below. According to standard flow classifications: a Reynolds number below 2000 indicates laminar flow, above 4000 indicates turbulent flow, and values between 2000 and 4000 correspond to transitional flow (Menon, 2015). The equation for calculating the Reynolds number is provided below:

$$Re = VL\rho/\mu$$

where the V is the fluid velocity (m/s). L is a diameter of the pipe (m). ρ is the density of fluid (kg/m^3) and μ is the dynamic viscosity of the fluid ($Pa \cdot s$).

Since the initial fracture space is rectangular rather than circular, the equivalent diameter can be calculated using the equation below (Figure A3 (a)) (Koch, 2008):

$$L = 1.30(ab)^{0.625}/(a + b)^{0.25}$$

where L is equivalent diameter (m). a is length of major side (m). b is length of minor side (m).

The Reynolds number at different flow rates for two initial fracture geometries (G-I and G-II) is illustrated in Figure A3 (b). In our experiments, we used flow rates of 3 mL/min and 9 mL/min, both of which fall within the laminar flow regime.

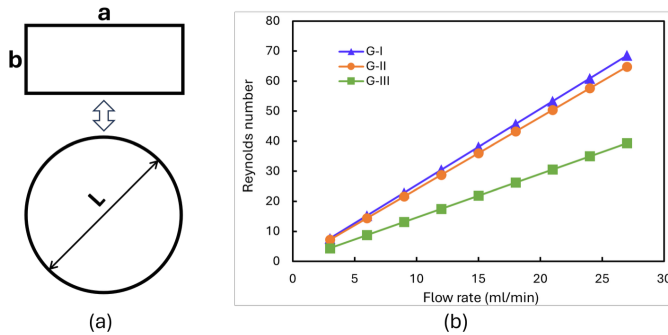


Figure A3. (a) The equivalent diameter of a rectangular tube; (b) Reynolds under different flow rates and initial fracture geometries.

A4: Fracture permeability evolution

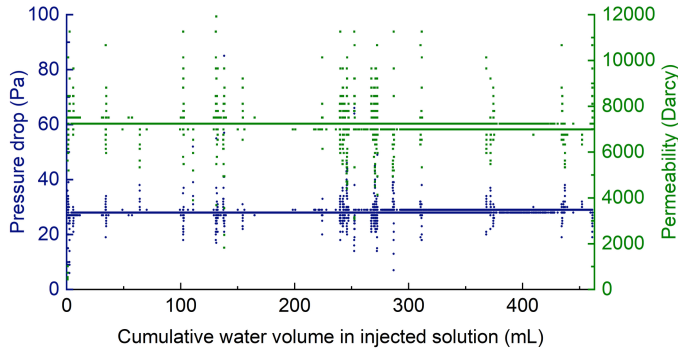


Figure A4. The evolution of pressure along the sample (blue dots) and the corresponding permeability (green dots) as a function of cumulative water volume in the injected solution for sample S3.

A5: Raw image and CT image processing

The following code processes camera images in the first four steps and micro-CT images in the subsequent three steps:

- 1) Sorts and renames the images based on their time differences.
- 2) Crops the images and converts them into a video.
- 3) Tracks the difference between each current image and the initial image.
- 4) Calculates the dissolution area by counting the white pixels.
- 5) Reads an STL file and generates a 3D surface plot along with a depth contour map.
- 6) Calculates the total reaction surface area as well as the areas of individual sections.
- 7) Calculates the total volume of the reaction surface, including the volumes of individual sections based on Z-axis ranges.

APPENDIX

Overall, different software tools are used to process the images of each sample acquired by the camera and micro-CT scanning. The workflow is outlined below:

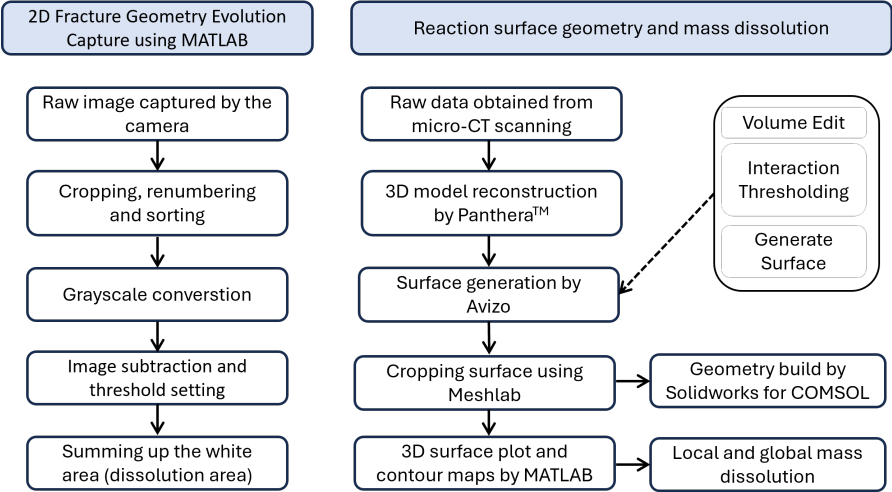


Figure A5. Image processing workflow.

A6: Fracture geometry after dissolution: S9 and S10 with duplicated tests S3 and S11

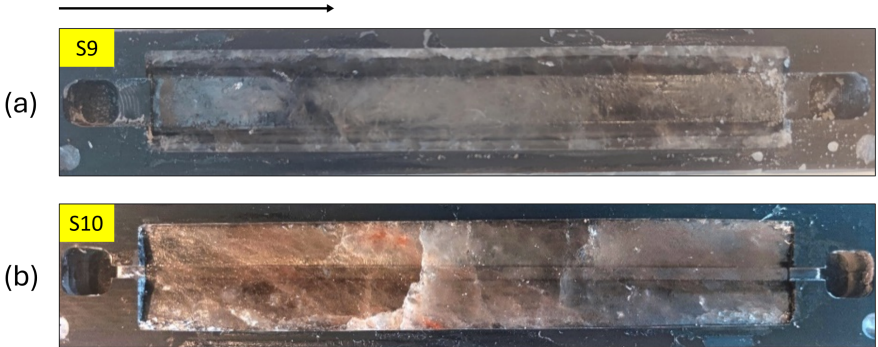
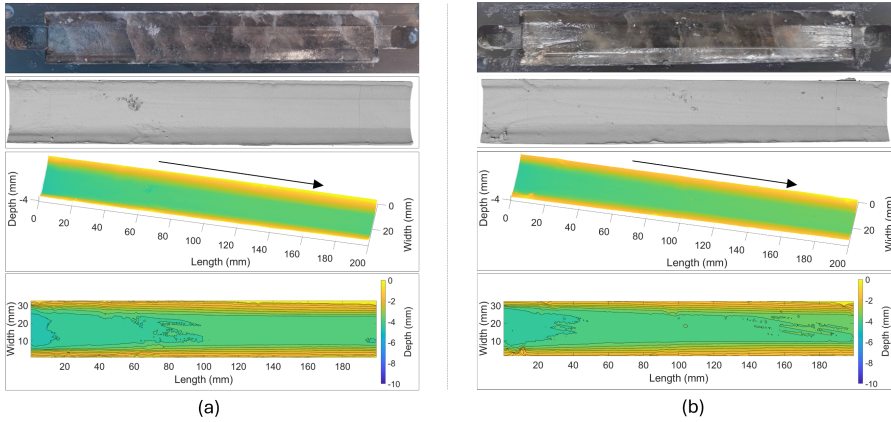
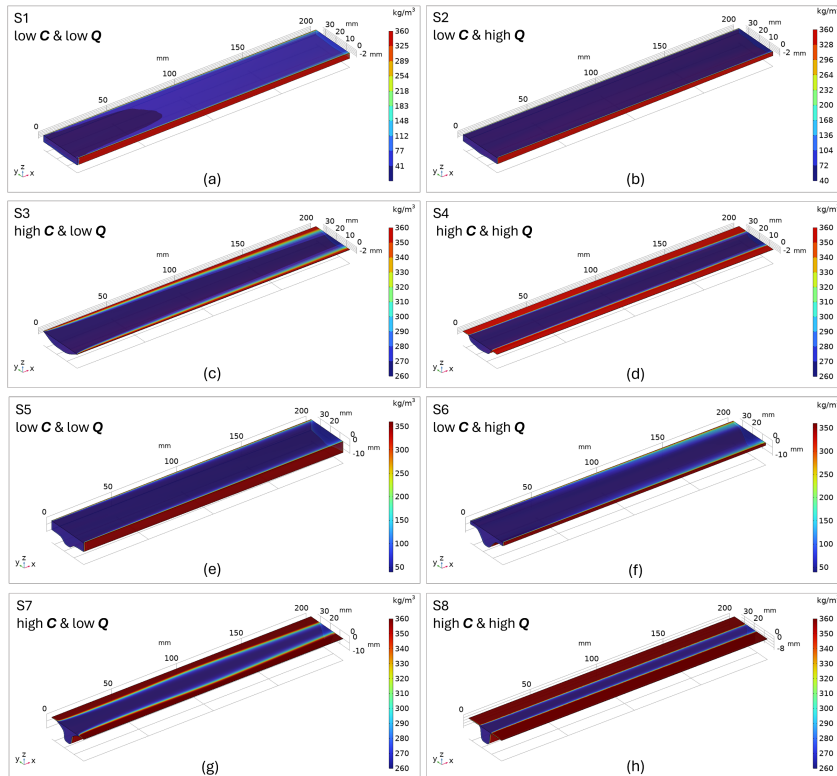


Figure A6. (a) and (b) show post-dissolution fracture geometries for samples S9 and S10, respectively.

To assess reproducibility, experiment S3 was duplicated as S11. A comparison of the post-dissolution fracture channel geometries shows a high degree of similarity (see Figure A7), confirming the reliability of the experimental procedure.



A7: Numerical simulation results



APPENDIX

A8: Péclet number-kinetic number calculation

Discussions on the impact of flow rate on fracture dissolution are often framed using the dimensionless Péclet (Pe) and Damköhler (Da) numbers. Below, we provide the equations and parameters used to calculate Pe and Da in our study.

$$Pe = v \langle b_0 \rangle / D_m$$

$$Da = K_s \langle b_0 \rangle / D_m$$

Table A2. Parameters for Pe and Da calculation

Parameters	Descriptions	Values
L0 (mm)	Channel length	200
W (mm)	Channel thickness	15
$\langle b_0 \rangle$	Initial average aperture	3.3
D_m	Molecular diffusion coefficient	1.61×10^{-9}
v	Initial average velocity	3.03×10^{-3} ; 1.01×10^{-3} ; 6.667×10^{-4} ; 9.375×10^{-3}
C_{eq} (g/L)	The equilibrium concentration of NaCl solution	360
C_{in} (g/L)	Inflow concentration of NaCl solution	40; 260; 300

The effective reaction rate coefficient for the aqueous species K is expressed as $k = 0.00489 C_{ini}^{-0.639}$, with C_{ini} representing the influent concentration. Based on this, the surface reaction rate constant K_s is obtained by multiplying K with the saturation concentration C_{sat} and the molar volume of NaCl (V_{mol}), giving $K_s = k \cdot C_{sat} \cdot V_{mol}$ (Zhou et al., 2022).

APPENDIX B

Appendix B presents supplementary microscope images of fracture surfaces supporting Chapter 3.

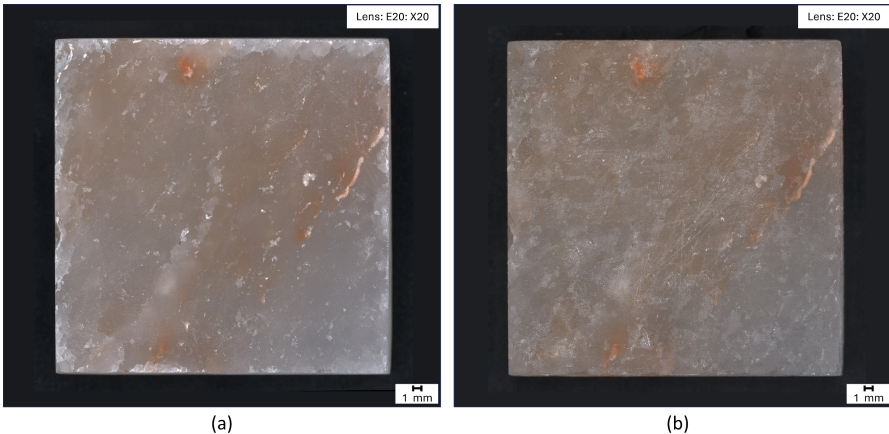


Figure B1. (a) and (b) show the complete profile of the fracture surface of W-T042-A before healing and after shearing.

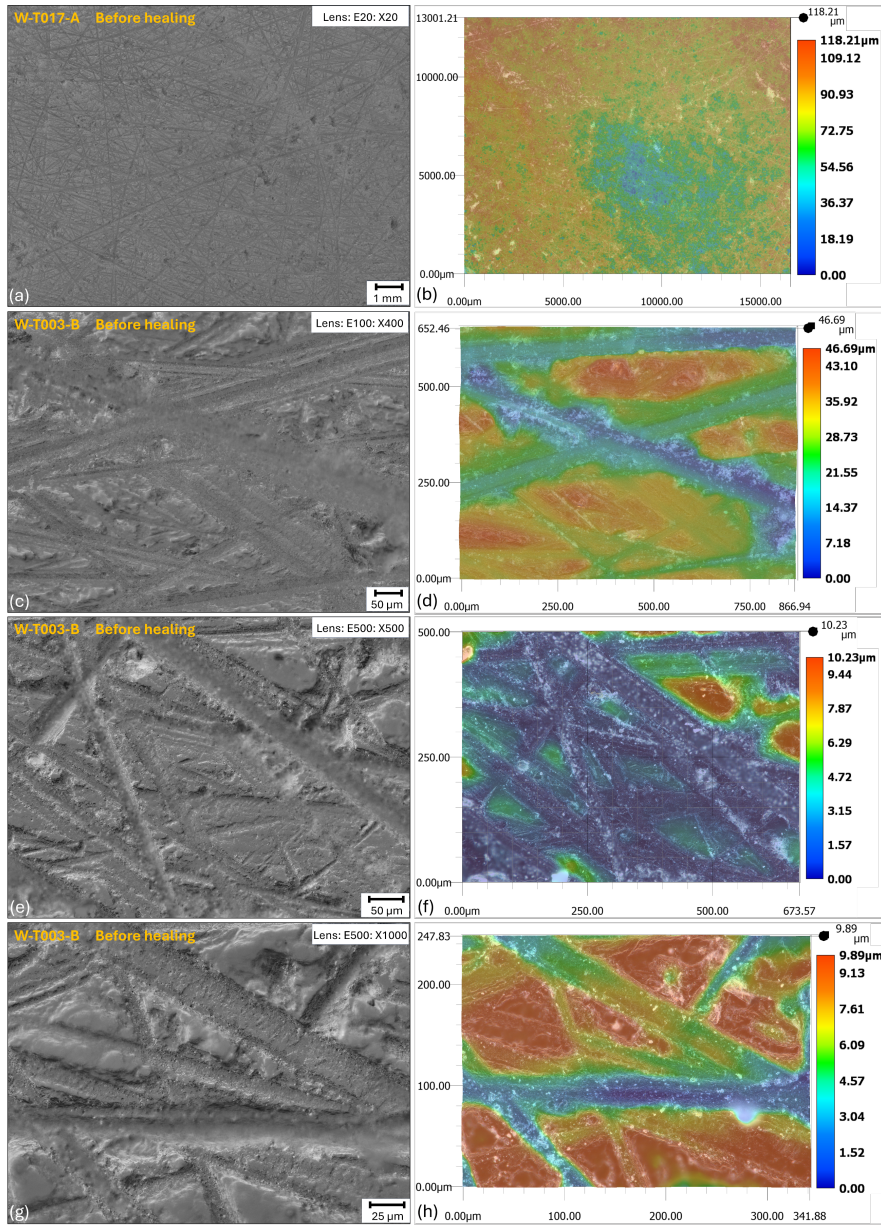


Figure B2. (a)-(h) present the microstructure of the fracture surface before healing at different magnifications. The left images show the edge-enhanced views, while the right panels display the corresponding 3D images. At 20 $\times$ magnification, the scratches appear randomly oriented with a curved overall pattern. At 100 $\times$ magnification and above, these scratches become more distinct, forming intersecting and connecting "channels".

APPENDIX C

All chapter related materials, including camera, microscope and micro-CT images, MATLAB scripts for image and data processing, are stored and organized in the 4TU ResearchData repository under the following DOI.

Chapter 2: Fu, Shihao; Dieudonné, Anne-Catherine; Bruhn, David; Li, Kai; Anne Pluymakers (2025): Experimental dataset on dissolution and transport process in rock salt fractures. Version 1. 4TU.ResearchData. dataset. <https://doi.org/10.4121/6aee6bff-524d-48cf-afe2-0a1f3fbaf2c4.v1>

Chapter 3: Fu, Shihao; Dieudonné, Anne-Catherine; Bruhn, David; Li, Kai; Anne Pluymakers (2025): Experimental dataset on strength recovery and microstructural observation in healed rock salt fractures. Version 1. 4TU.ResearchData. dataset. <https://doi.org/10.4121/1417282f-8d59-4d75-affc-1b66cd0a8d9a.v1>

Chapter 4: Fu, Shihao; Dieudonné, Anne-Catherine; Bruhn, David; Li, Kai; Anne Pluymakers (2025): Experimental data on the healing behavior of rock salt fractures with different surface roughness. Version 1. 4TU.ResearchData. dataset. <https://doi.org/10.4121/a2aa4b75-d277-4985-b809-7ee41fc57b7b.v1>

ACKNOWLEDGEMENT

My PhD journey began four and a half years ago, and it was also my first experience living abroad. I still remember the day I landed at Schiphol Airport, the crisp autumn weather, the flat green landscape, and the remarkably tall people all around me. Over time, I grew accustomed to both academic life and everyday living in Delft. Looking back now, I can say it has been a truly wonderful journey, rich with friendships, knowledge, and personal growth. I could not have completed it without the support of many people, and I would like to express my gratitude to everyone who guided and encouraged me along the way.

First, I would like to express my gratitude to the China Scholarship Council (CSC). Without its financial support, completing my doctoral studies would not have been possible. I also thank TU Delft for providing funding, a supportive working environment, and well equipped laboratory facilities.

I want to thank Dr. Anne Pluymakers. Your energy and motivation have been truly inspiring, and working with you has been an amazing experience. We had numerous meetings during my PhD, and I still remember how you wrote and drew out every key point to help me understand. You gave me inspiration for experimental design, suggested effective methods to analyse the results, and supported me through countless rounds of revision during the publication process. You also encouraged me to attend conferences and workshops, which helped me grow professionally. I would say that the overall framework of this thesis still reflects your vision. After four years, I have developed many ideas for future research and I am now clearer about what I want to achieve in my future career.

I also want to express my sincere thanks to Dr. Anne-Catherine Dieudonné. At the beginning of my PhD, I focused on learning numerical modelling through our Lagamine meetings. You always ran the simulations and solved problems with impressive speed and clarity, almost like a magician. Whether it was experimental work or numerical modelling, you consistently helped me identify issues and improve my approach. Often, I could not answer your questions immediately during meetings, and that was a clear reminder that I needed to deepen my understanding. Your ability to catch subtle errors has always amazed me. It has been a privilege to have you as my supervisor.

I would also like to thank Prof. Dr. David Bruhn. You are energetic and approachable, and I have truly enjoyed our conversations. Even with your packed schedule, you always made time to meet and discuss my progress, which I deeply appreciate. You brought fresh ideas, suggested possible directions for my research, and reminded me to be more confident. Your encouragement helped me move forward during uncertain times.

To the members of the Rock Mechanics and Petrophysics Laboratory, I thank Dr. Auke Barnhoorn for organizing the lab meetings. Kai, Chris, Milad, Debanjan, Aukje, Parvin, Entela, Jop, Taka, and Jesse, thank you for the enjoyable weekly discussions where ideas flowed freely. Even though I did not speak much, I truly enjoyed listening to your presentations and sharing everyday moments with you. The conversations and laughter made the research environment warmer and more inspiring, especially during the Covid period.

ACKNOWLEDGEMENT

I am also very grateful to the lab technicians whose support made my experiments possible. I appreciate Jelle Kampf for his essential help in designing and preparing the dissolution experiments, and Michiel and Sian for their support with the initial preparation work at the start of my PhD. I also acknowledge Ellen, Arjan, and Joost for assistance with sample visualization; Christian and Karel for teaching me how to use the shear box and helping me troubleshoot signal issues; and Marc for preparing the rock salt plates. Jinbao, your guidance on the 3D surface scans using the microscope was incredibly helpful in the later stages of my research. I also thank Dr. Dominique Ngan-Tillard for providing the workstation used to process the CT scan images.

I would like to thank the support staff of the department, Marlijn, Barbara, and Ralf, who always greeted me warmly whenever I approached them with questions or practical matters. To my friends and colleagues Jingming, Maria, Sepideh, Sverre, Yusuke, David, Alireza, Mohammad, Suzanne, Ilshat, Alex, Eddy, Boris, Selvi, Zhaojiang, Lexin, Fan, Bhini, Ties, Wen, Na, Vidushi, Wei, and Aoxi, thank you for all the conversations and drinks we shared. Mahmoud, Lifei, Guofeng, and Jianxin, thank you for the fun moments playing table tennis and badminton. It was the perfect way to relax when writing my thesis. Fanxiang, Ziliang, Mengjie, Hang, and Wencan, I really enjoyed the many dinners we shared, as well as the card games we played together. To my friends and supervisors from my high school, bachelor's, and master's years, thank you for staying in touch and sharing life updates despite the distance. Your continued support has meant a lot.

I want to thank my fiancée, Bing Xu, who is pursuing a PhD in Applied Science and will soon be a doctor. The second year of my PhD was the most difficult for me, and your companionship and support helped me get through it. I still remember how you cared for me during two bouts of Covid, and how you kept me focused and strong when I struggled. I feel incredibly lucky to have you in my life. We have travelled to more than ten countries together, and there are still so many beautiful places left to explore. With you, I feel more confident and brave, and I truly look forward to building our life together.

I also want to express my sincere thanks to my parents in law, Jianqin Xia and Jianrong Xu. Without your support, encouragement, and trust. I would not have come this far.

Most of all, I want to thank my family. I know it was not easy for you when I left for the Netherlands. My mother, Ailian Sun, you often could not sleep well after I left, but over time you have come to feel more at peace with it. My sister, Wei Fu, thank you for always respecting my decisions and for supporting me without hesitation whenever I faced challenges.

There are many more people who helped me along the way, and even if I cannot name everyone here, please know that I carry your kindness and support with me. Last but not least, Delft is a beautiful place. The landscapes I experienced, from green trees and peaceful lakes and canals to the rolling sea, the gentle summer breeze, and the rain and snow of winter, have created many unforgettable moments. I will always cherish my time at TU Delft and in the Netherlands.

CURRICULUM VITAE

Shihao FU (付世豪)

10-10-1995 Born in Hu Bei, China.

EDUCATION

Sep 2014 - Jun 2018	Bachelor's Degree, Petroleum Engineering Yangtze University (Wu Han)
Sep 2018 - Jun 2021	Master's Degree, Oil & Gas Well Engineering China University of Petroleum (Bei Jing)
Sep 2021- Feb 2026	Ph.D. Rock mechanics Delft University of Technology (TU Delft), the Netherlands <i>Thesis: Evolution of rock salt fracture geometry and mechanical properties during fluid-rock interactions</i> Promotor: Prof. dr. D.F. Bruhn Copromotor: Dr. A.M.H. Pluymakers Copromotor: Dr.ir. A.C. Dieudonné

LIST OF PUBLICATIONS

JOURNALS

2. Fu, S., Li, K., Dieudonné, A. C., Bruhn, D. and Pluymakers, A. Effects of Fluid Conditions and Fracture Geometry on Rock Salt Fracture Evolution. (under preparation).
1. Fu, S., Dieudonné, A. C., Bruhn, D., Li, K. and Pluymakers, A. Fracture healing and surface roughness evolution in rock salt. (under preparation).

CONFERENCES

2. Fu, S., Dieudonne, A.C., Bruhn, D. and Pluymakers, A., 2025. Healing behavior of rock salt fracture with varying surface roughness. The Mechanical Behavior of Salt XI, p.24.
1. Fu, S., Dieudonne, A.C., Bruhn, D. and Pluymakers, A., 2025. Shear strength recovery of rock salt fractures following healing process. 8th International Conference on Coupled THMC Process, Nicosia, Cyprus.

