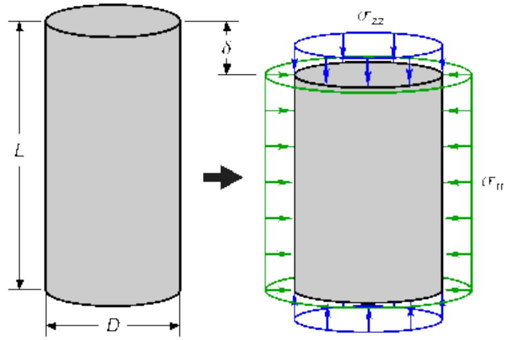
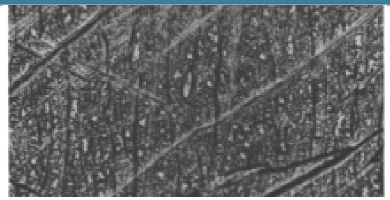
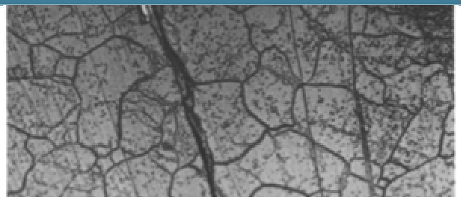
SAND2022-8511C

Sandia National Laboratories

A New Constitutive Model for Rock Salt Viscoplasticity







Benjamin Reedlunn

Materials and Failure Modeling Department

June 27th, 2022

56th U.S. Rock Mechanics Symposium

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U.S. DEPARTMENT OF ENERGY NNSA

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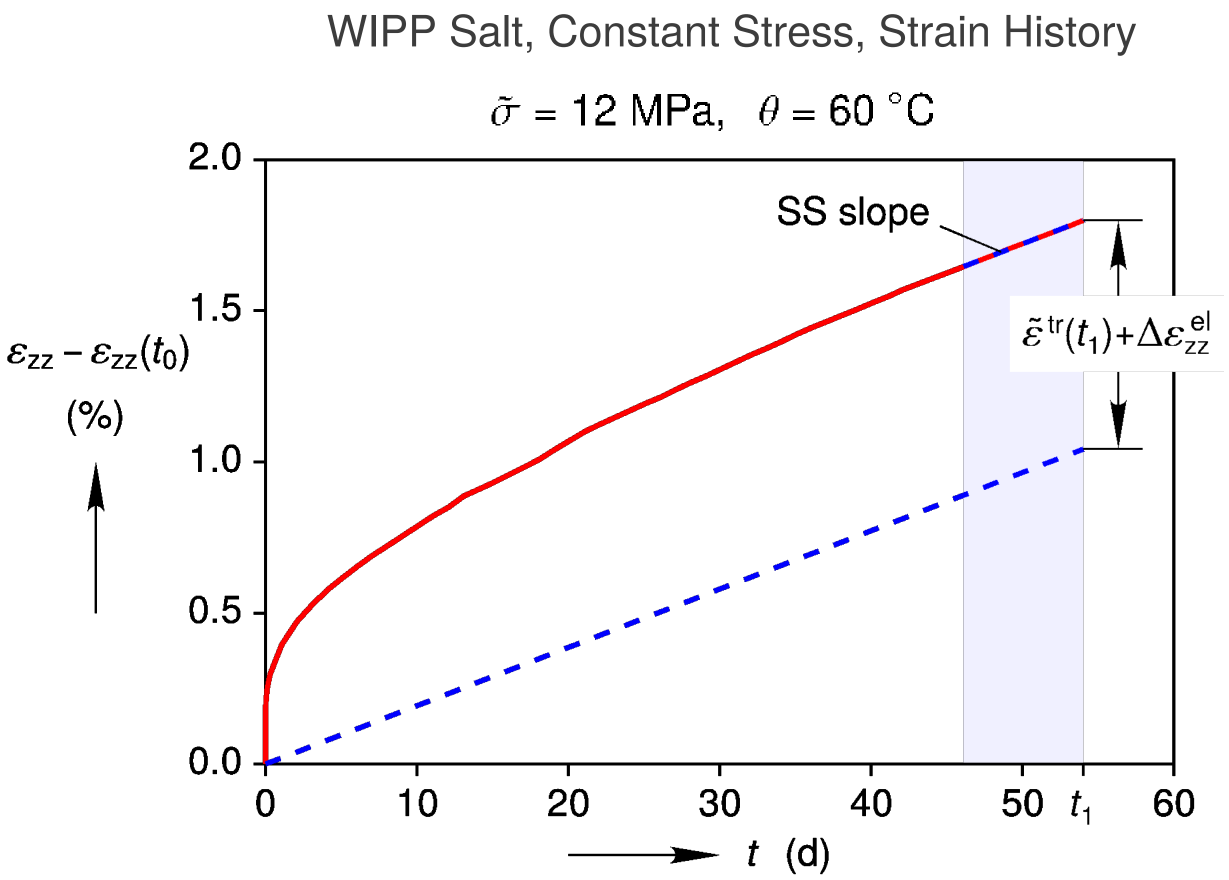
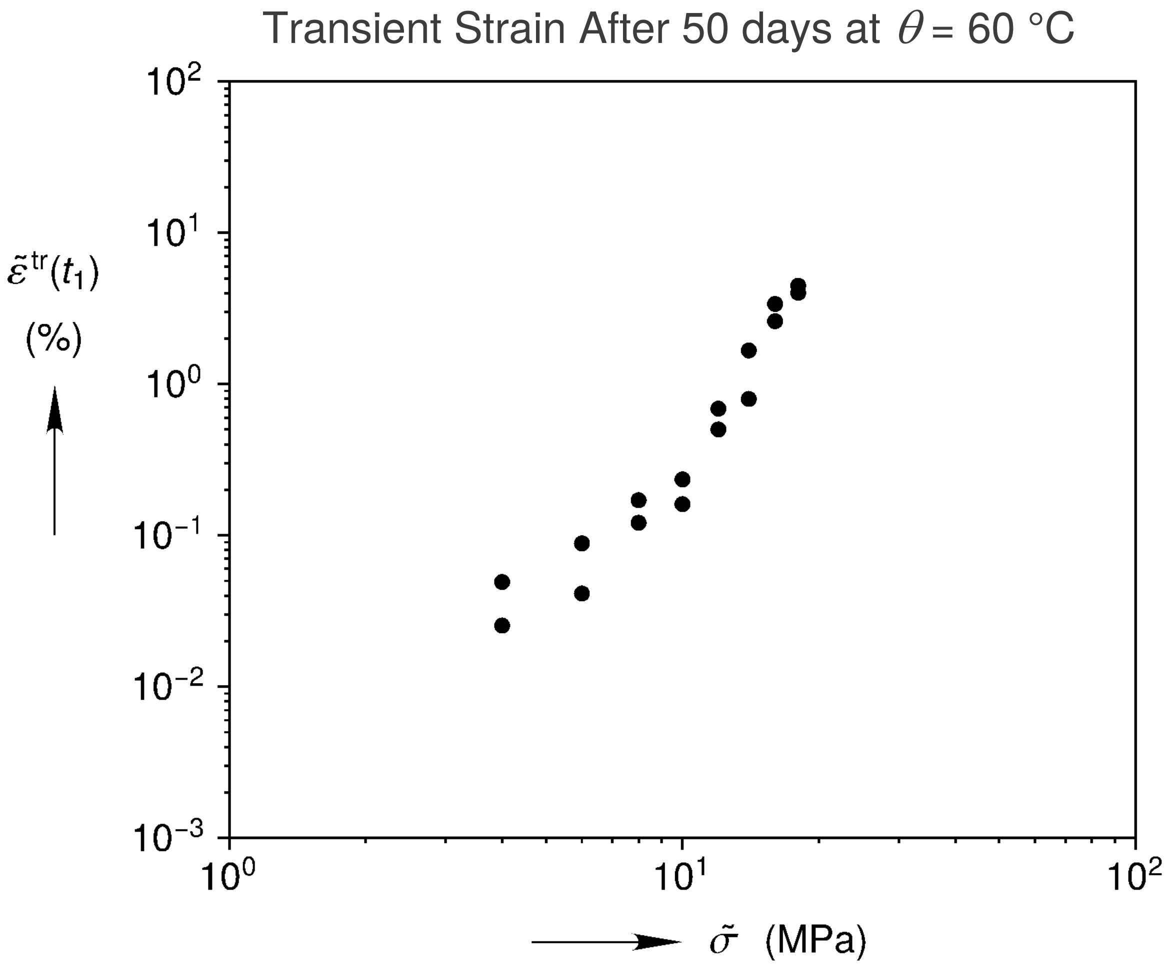
Background

Motivation

1. Dozens of existing salt constitutive models
   1. Phenomenological to micro-physically based
   2. Simple vs. full featured
2. My model priorities
   1. Phenomenological, yet motivated by micro-physical observations
   2. Conforms to the framework of Rational Thermodynamics
   3. Captures viscoplasticity, damage, and healing
   4. Captures viscoplastic hardening behavior
      1. Hardening transition from low to medium stresses (strain rates)
      2. Hardening transition from medium to high stresses (strain rates)
      3. Re-hardening during non-monotonic loading

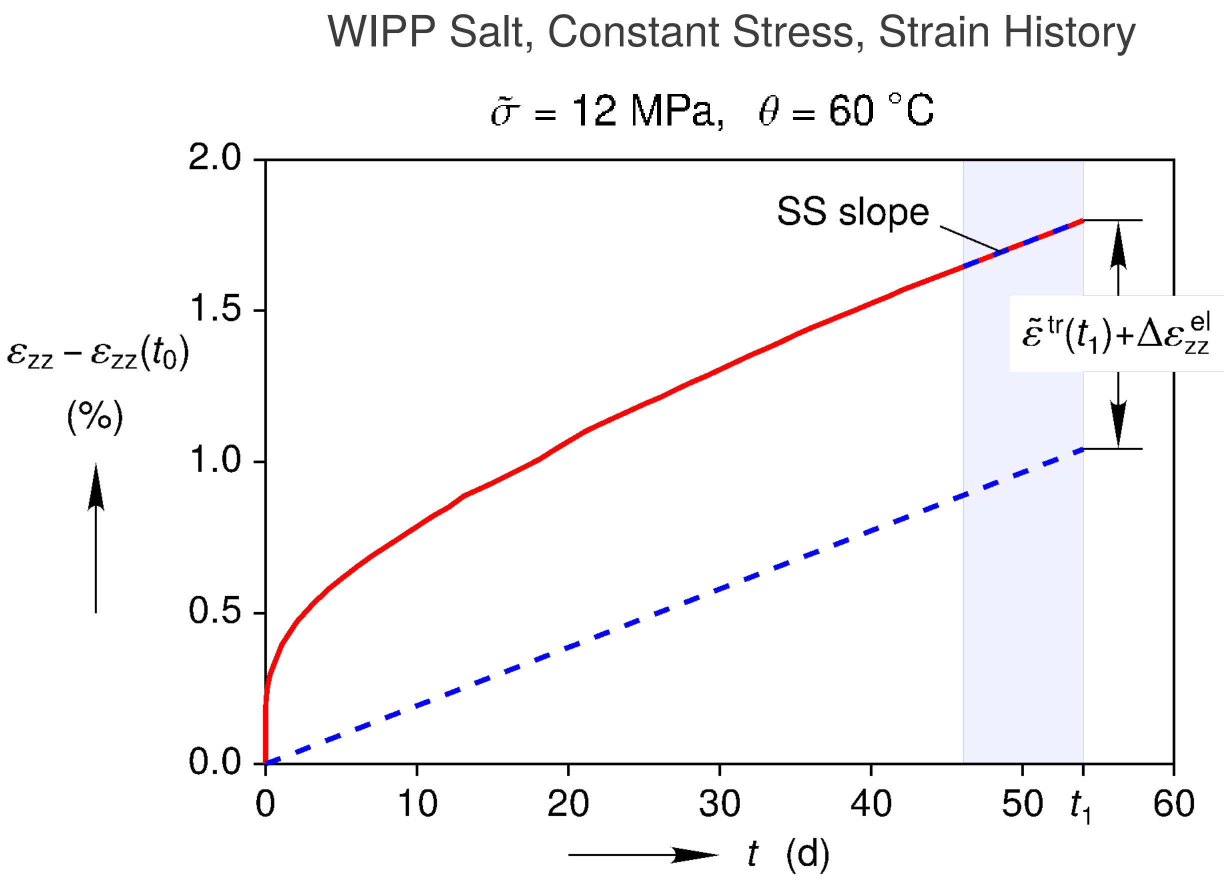
Hardening Transition from Low to Medium Stresses (Strain Rates)

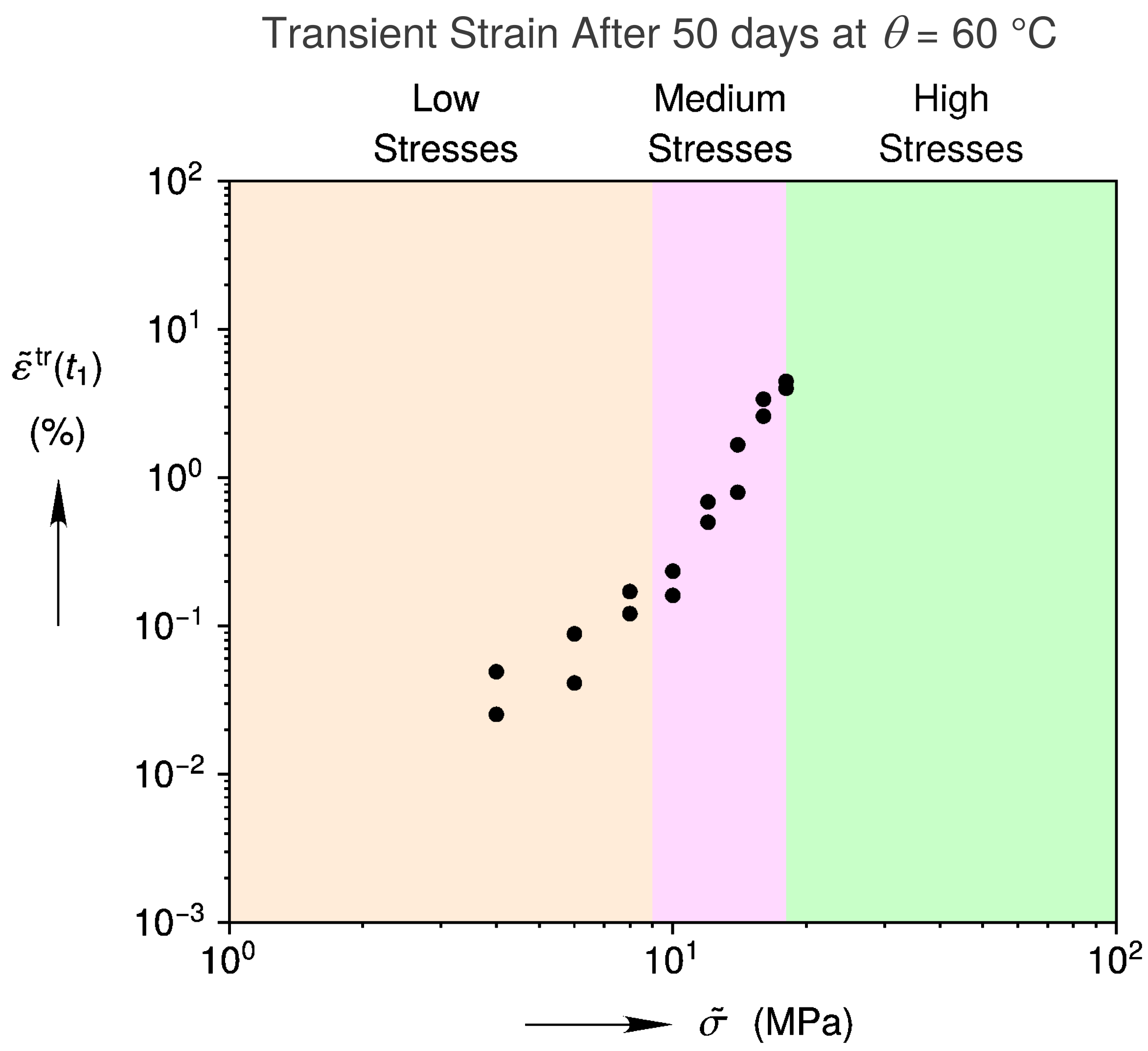




Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

Hardening Transition from Low to Medium Stresses (Strain Rates)





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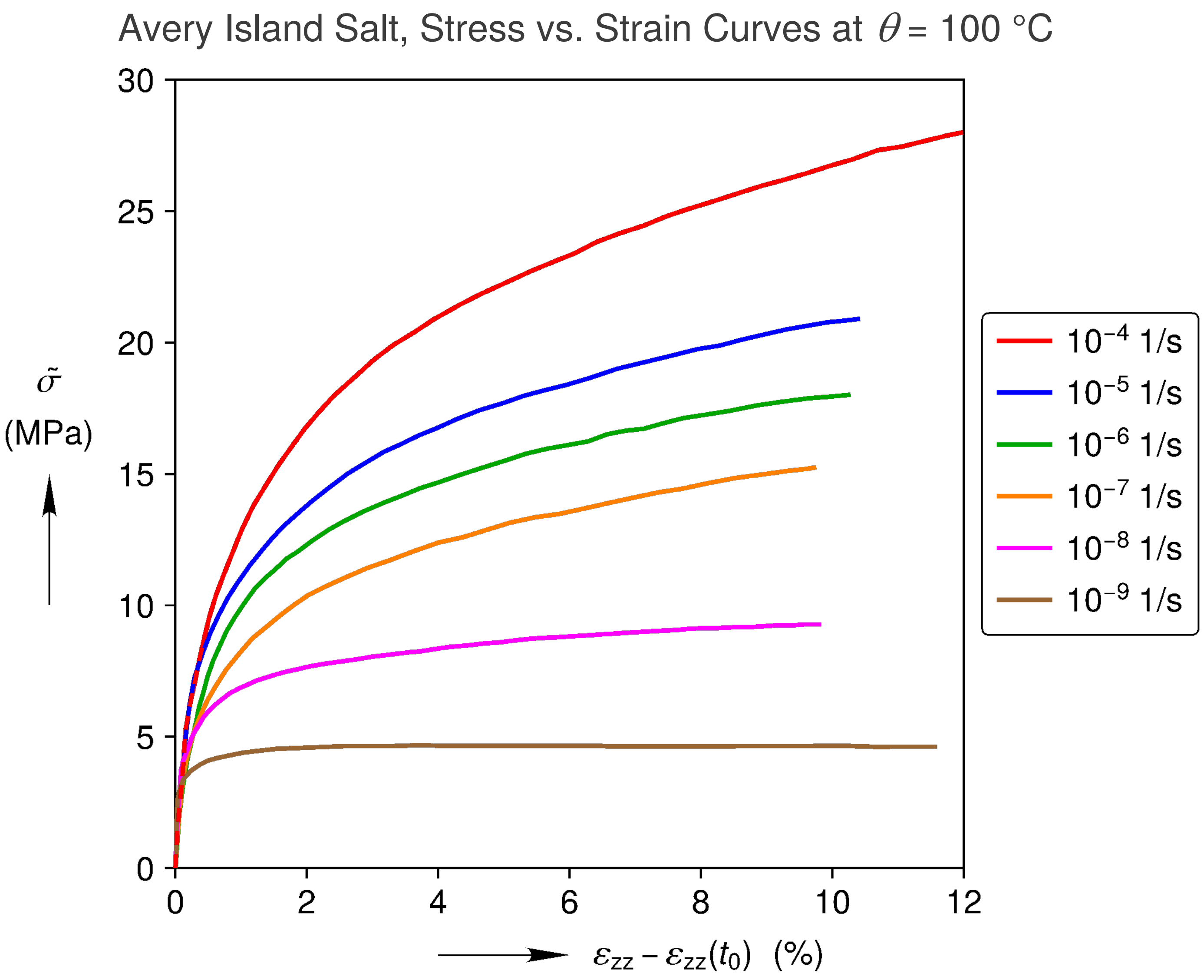
Hardening Transition from Medium to High Strain Rates (Stresses)



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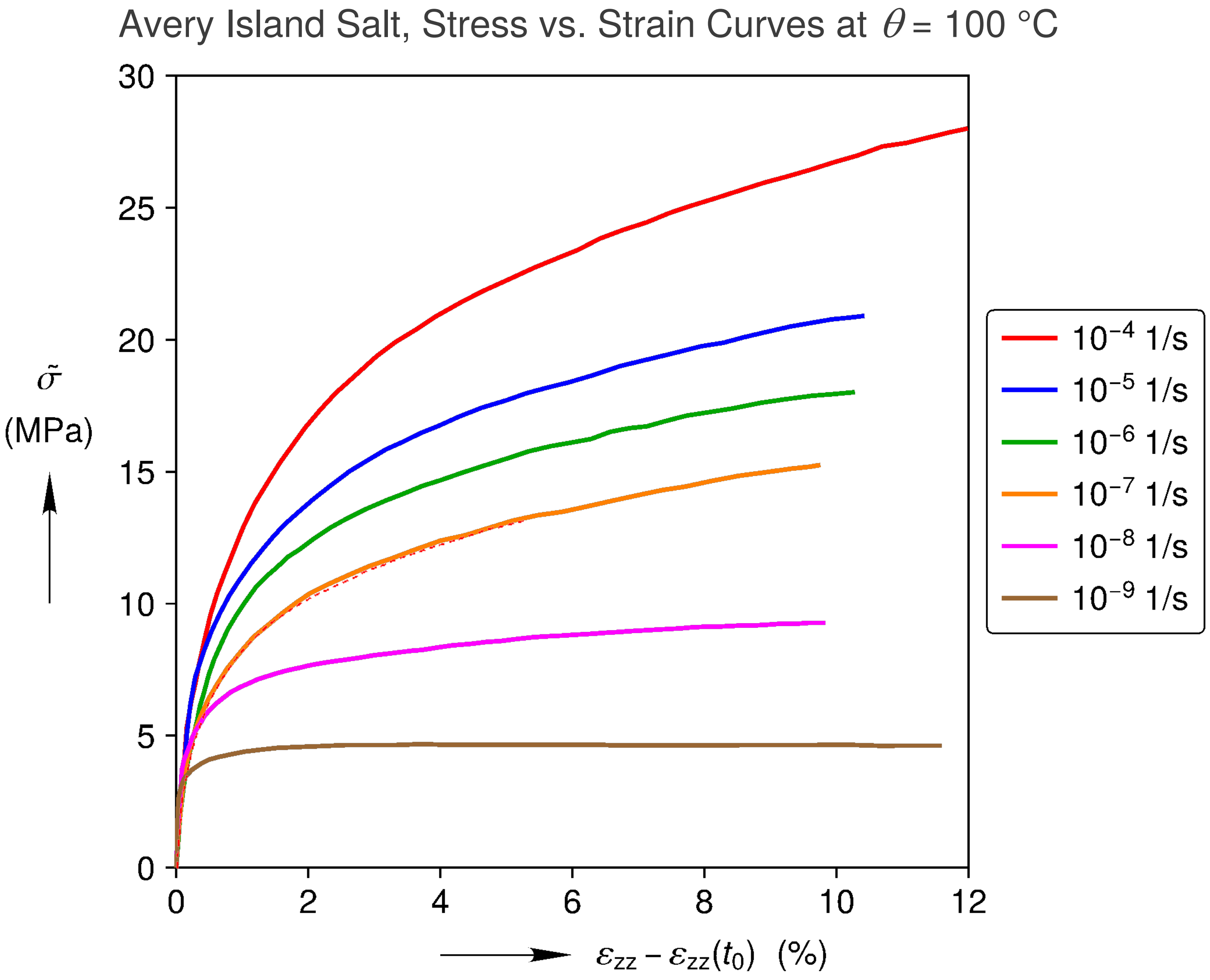

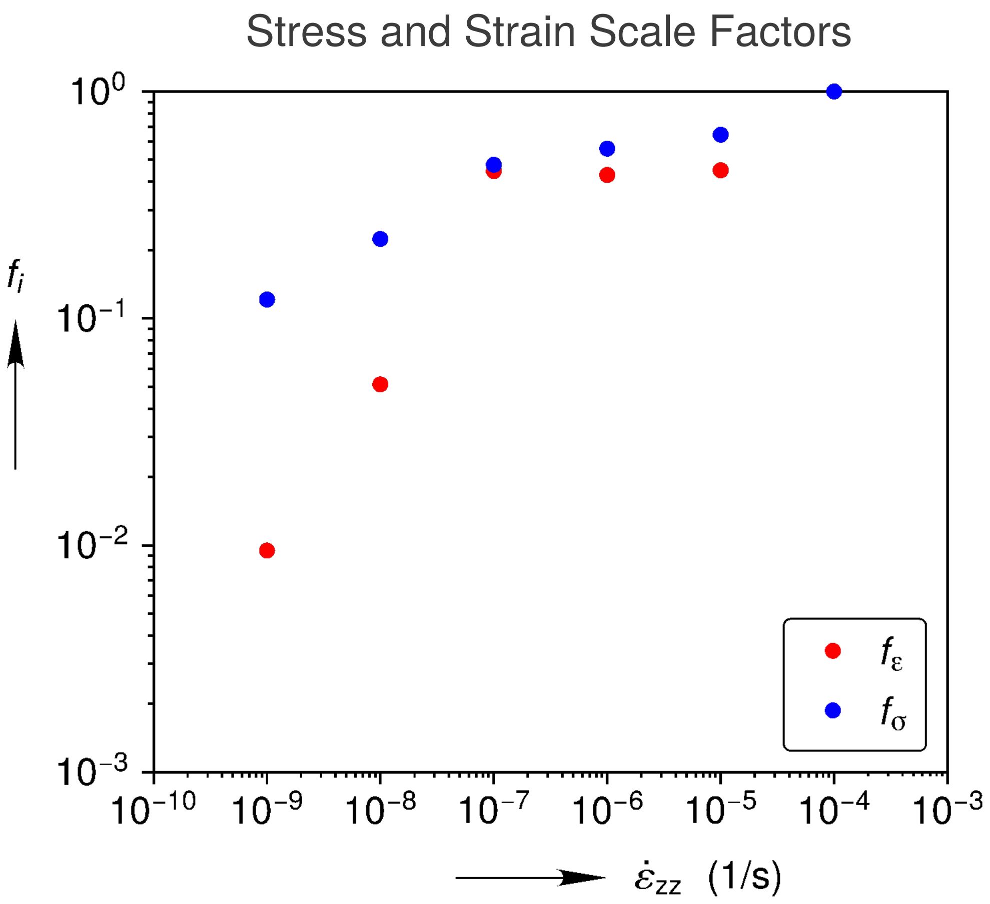

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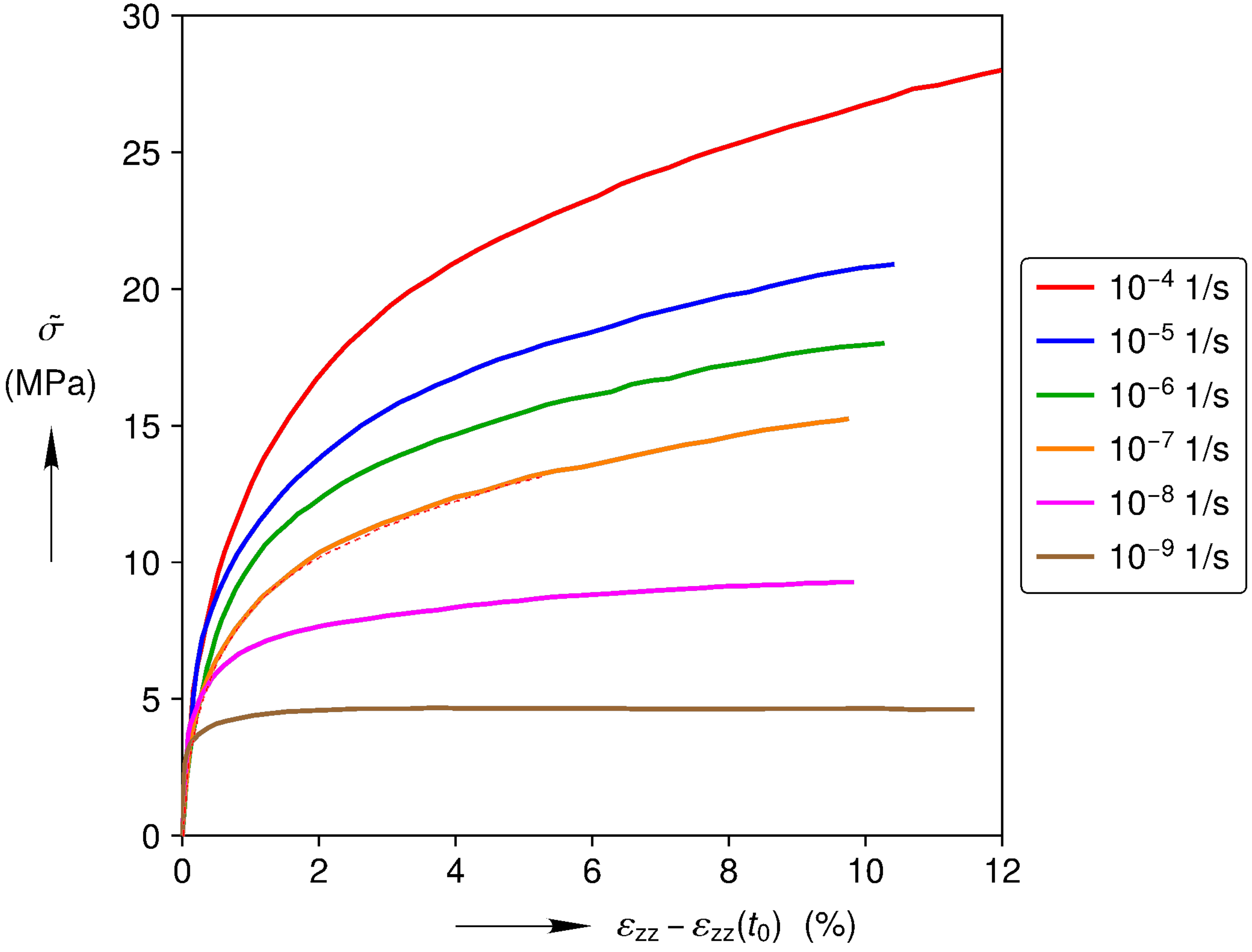
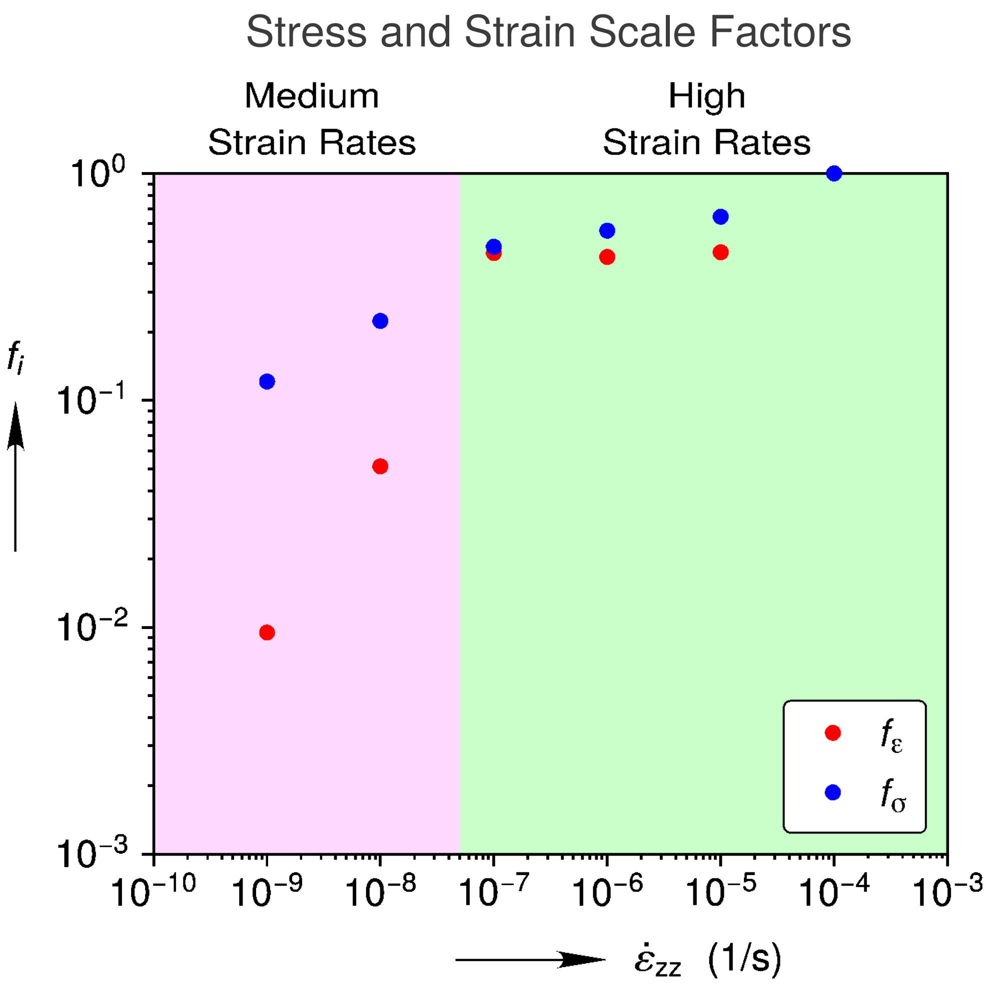
Hardening Transition from Medium to High Strain Rates (Stresses)

Avery Island Salt, Stress vs. Strain Curves at $\theta = 100$ °C





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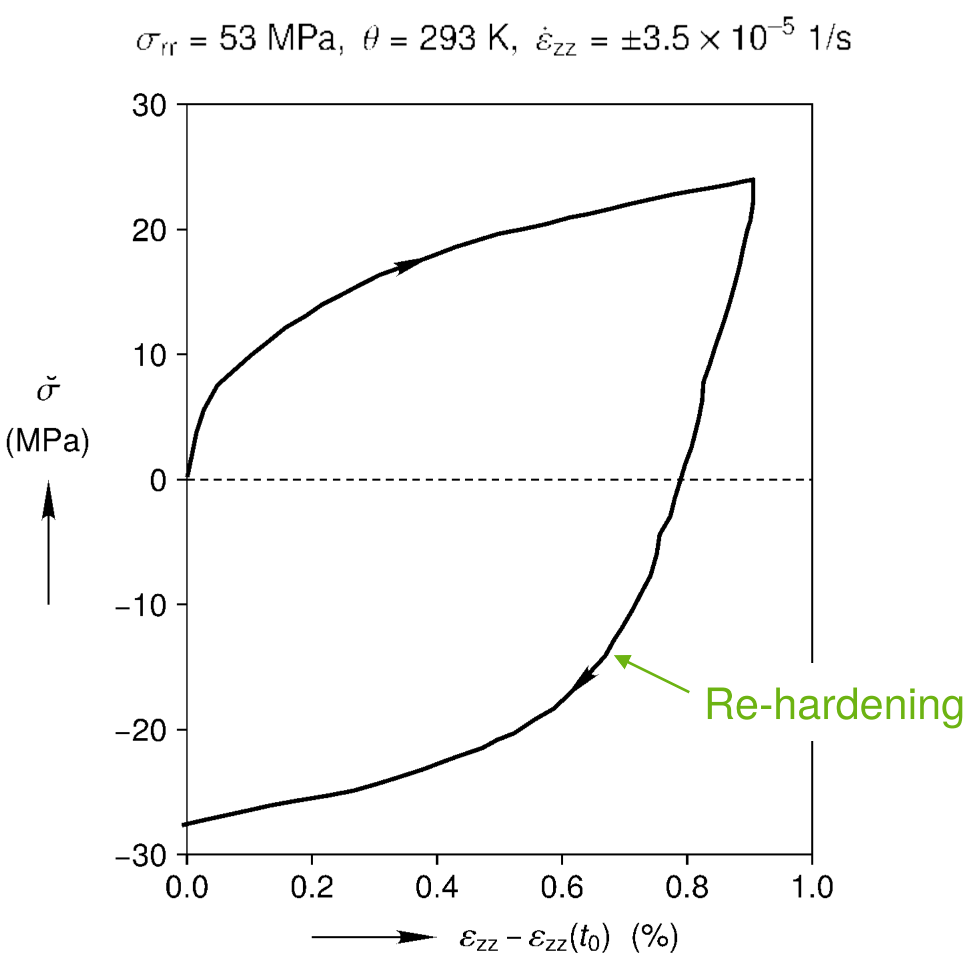
Re-hardening During Non-Monotonic Loading

Constant Strain Rate Test on Artificial Salt



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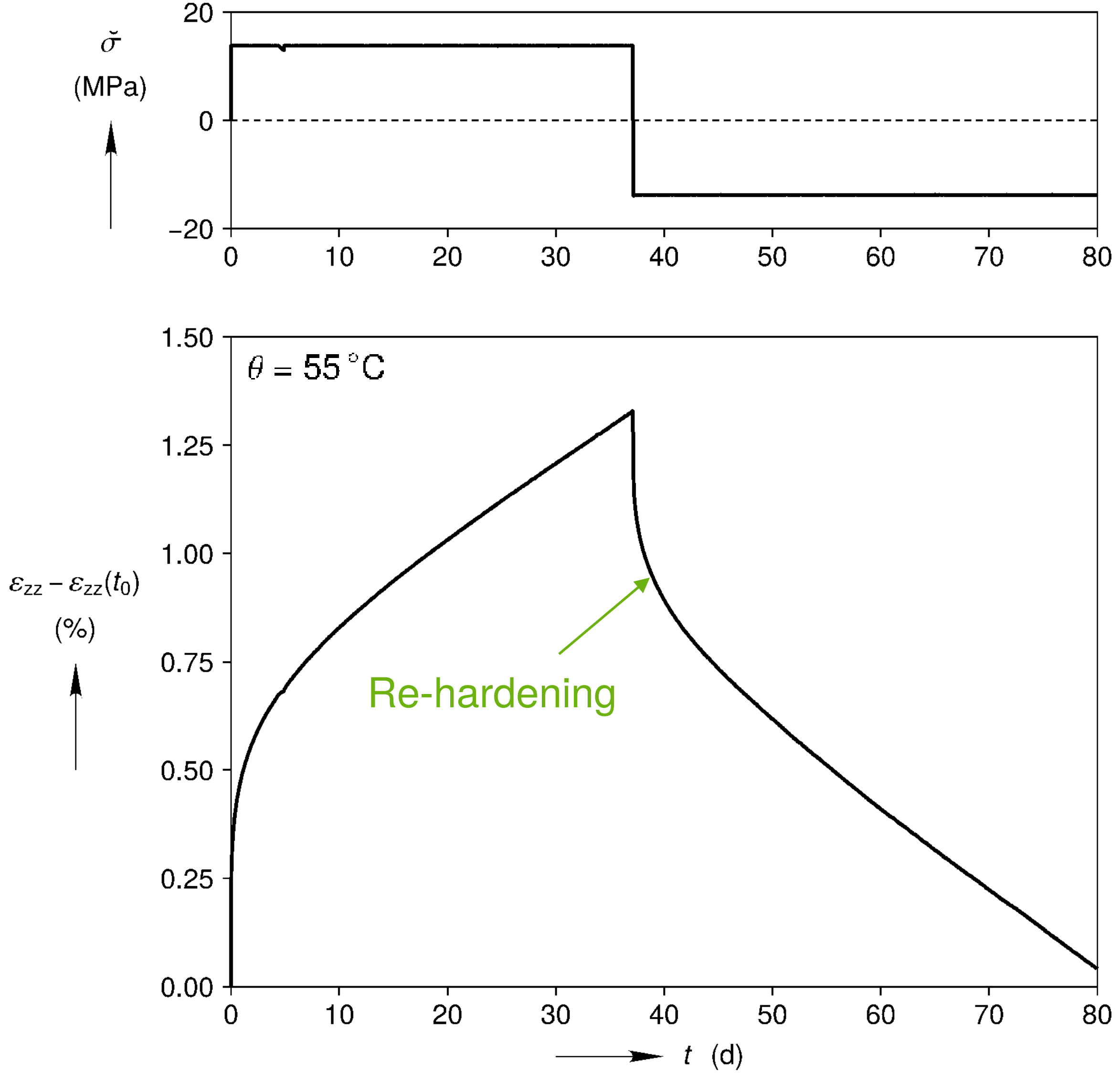
Multi-Stage Constant Stress Test on Cayuta Salt

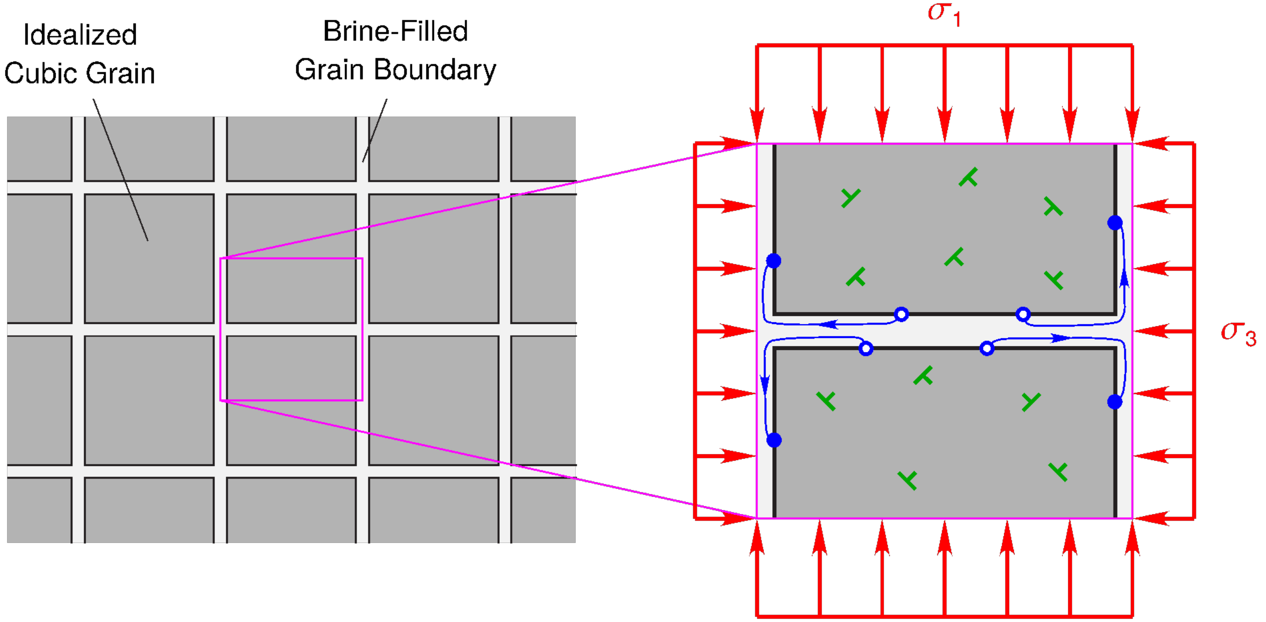


Experimental measurements from: Mellegard et al. (2007)

Model Overview

Viscoplastic Branches

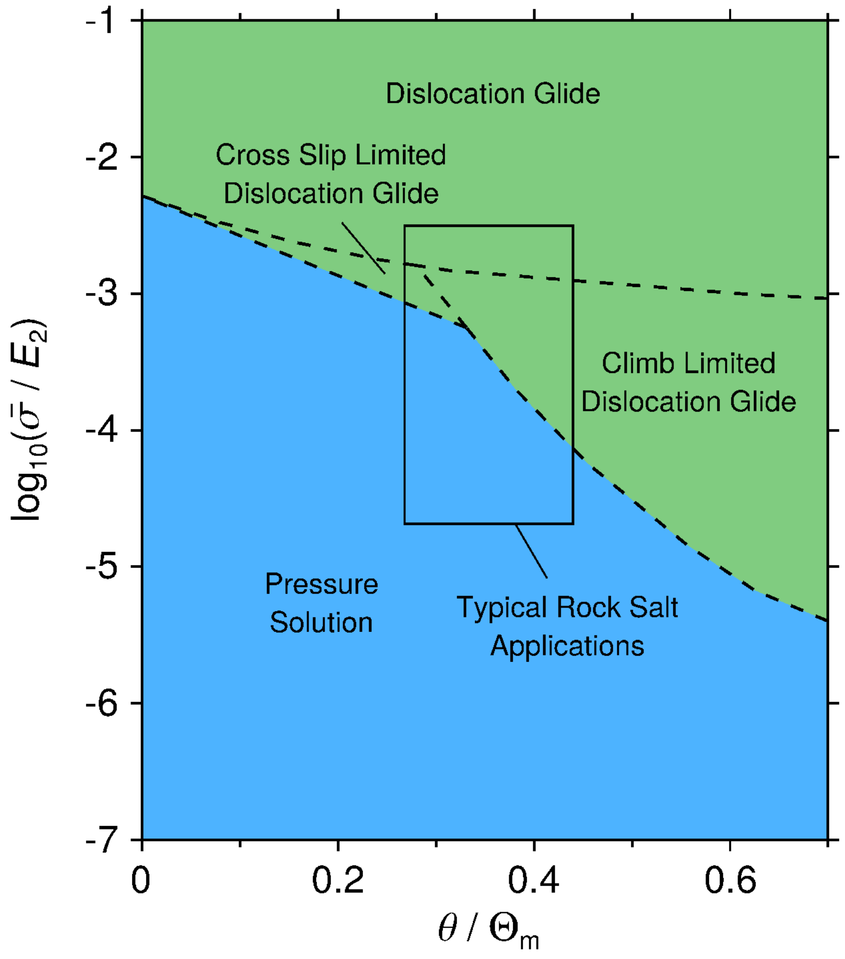
Pressure Solution and Dislocation Glide



Strain Rate Decomposition
(proportional, monotonic, loading)

$$\dot{\tilde{\varepsilon}}^{vp} = \dot{\tilde{\varepsilon}}^{ps} + \dot{\tilde{\varepsilon}}^{dg}$$

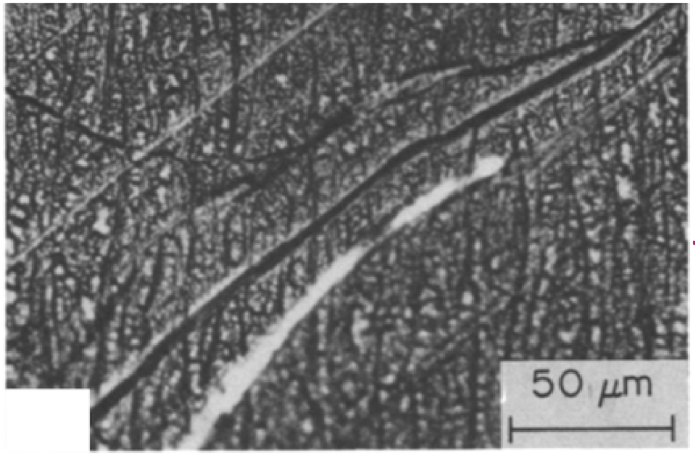
A (Rough) Steady-State
Deformation Mechanism Map



Θ_m = 1077 K
E_2 = 10 GPa
Average grain size = 10 mm

Microstructural Observations

Wavy Slip Bands



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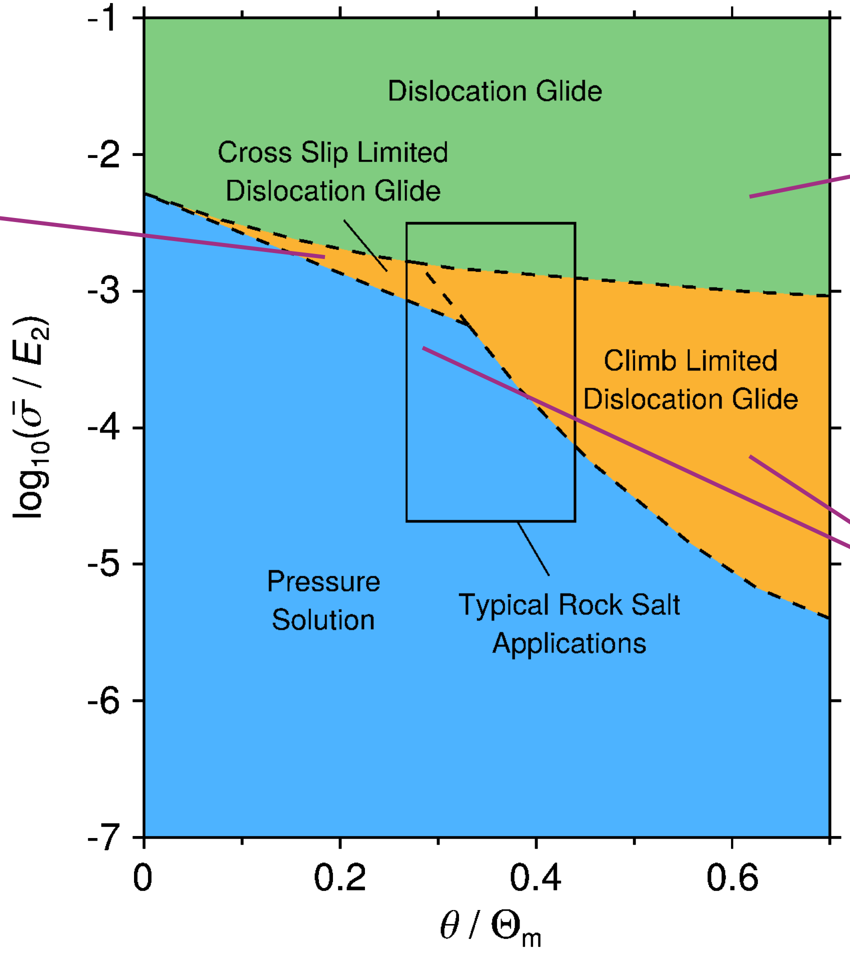
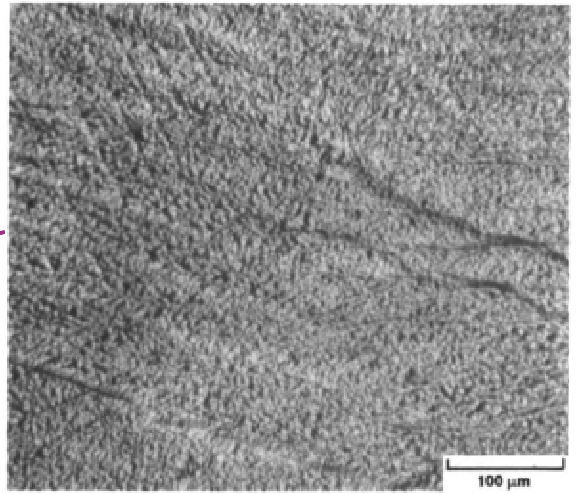
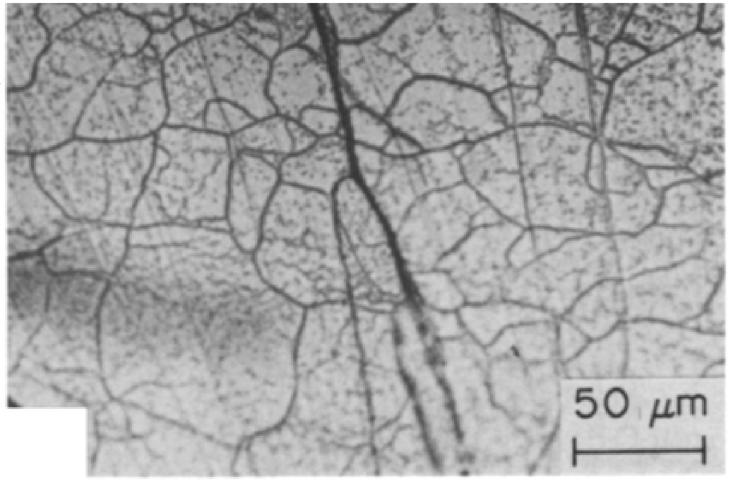


Θ_m = 1077 K
E_2 = 10 GPa
Average grain size = 10 mm

Uniform Dislocation Density



Subgrains



Raj, S. V. and Pharr, G. (1989). "Creep substructure formation in sodium chloride single crystals in the power law and exponential creep regimes". In: Materials Science and Engineering: A 122.2, pp. 233–242.

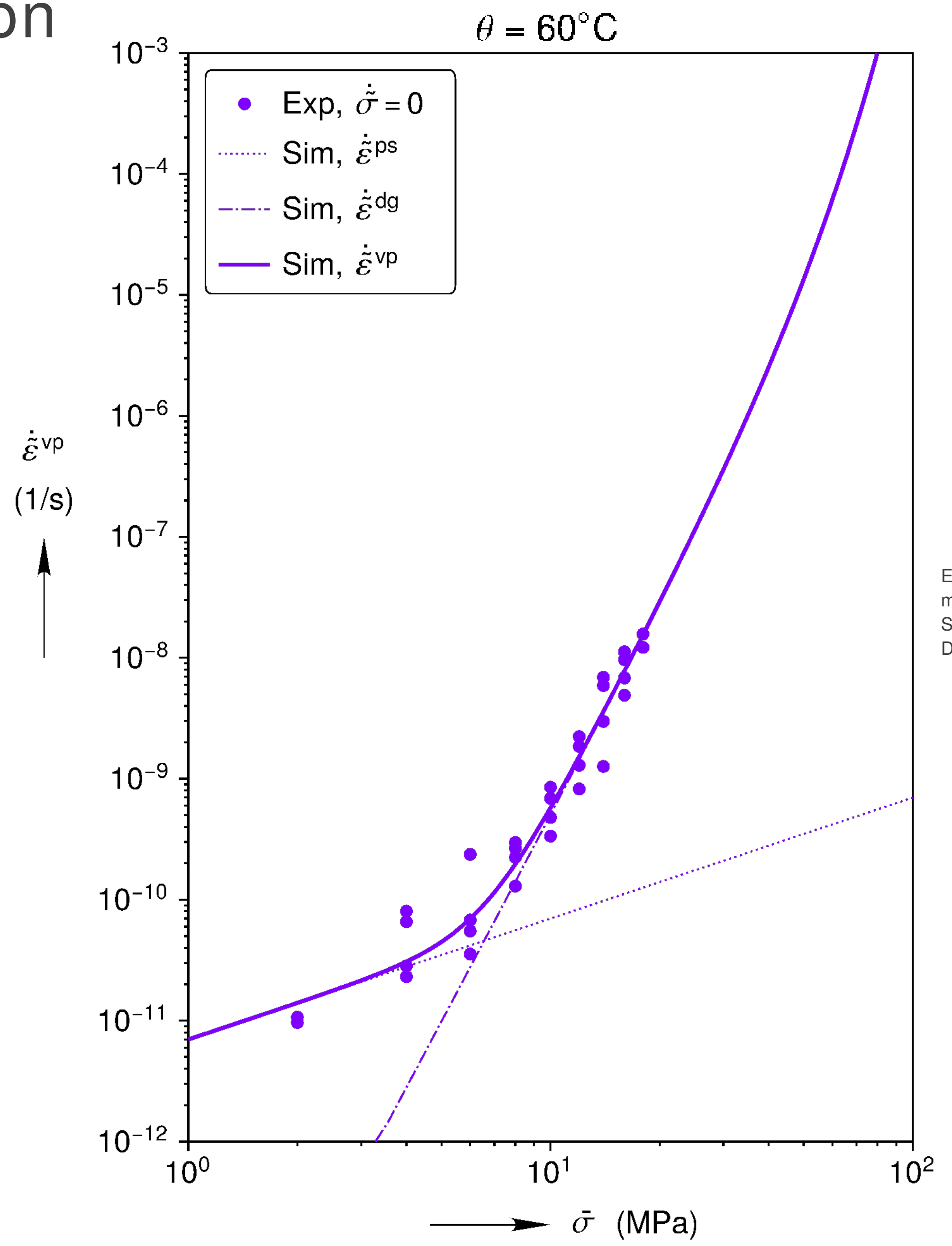
Carter, NL, Horseman, ST, Russell, JE, and Handin, J (1993). Rheology of rocksalt. Journal of Structural Geology. Vol 15. No 9-10. pp 1257-1271.

Steady-State Strain Rate Calibration

Steady-State Strain Rates

$$\dot{\tilde{\varepsilon}}^{ps} = P_1 \exp\left(-\frac{P_2}{\theta}\right) \frac{\tilde{\sigma}}{\theta}$$

$$\dot{\tilde{\varepsilon}}^{dg} = Y_3 \exp\left(-\frac{G_2}{\theta}\right) \left[\sinh\left(\frac{\tilde{\sigma}}{Y_4}\right)\right]^{Y_5}$$



Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

Spiers, C., Schutjens, P., Brzesowsky, R., Peach, C., Liezenberg, J., and Zwart, H. (1990). Experimental determination of constitutive parameters governing creep of rocksalt by pressure solution. In: Geological Society, London, Special Publications 54.1, pp. 215–227.

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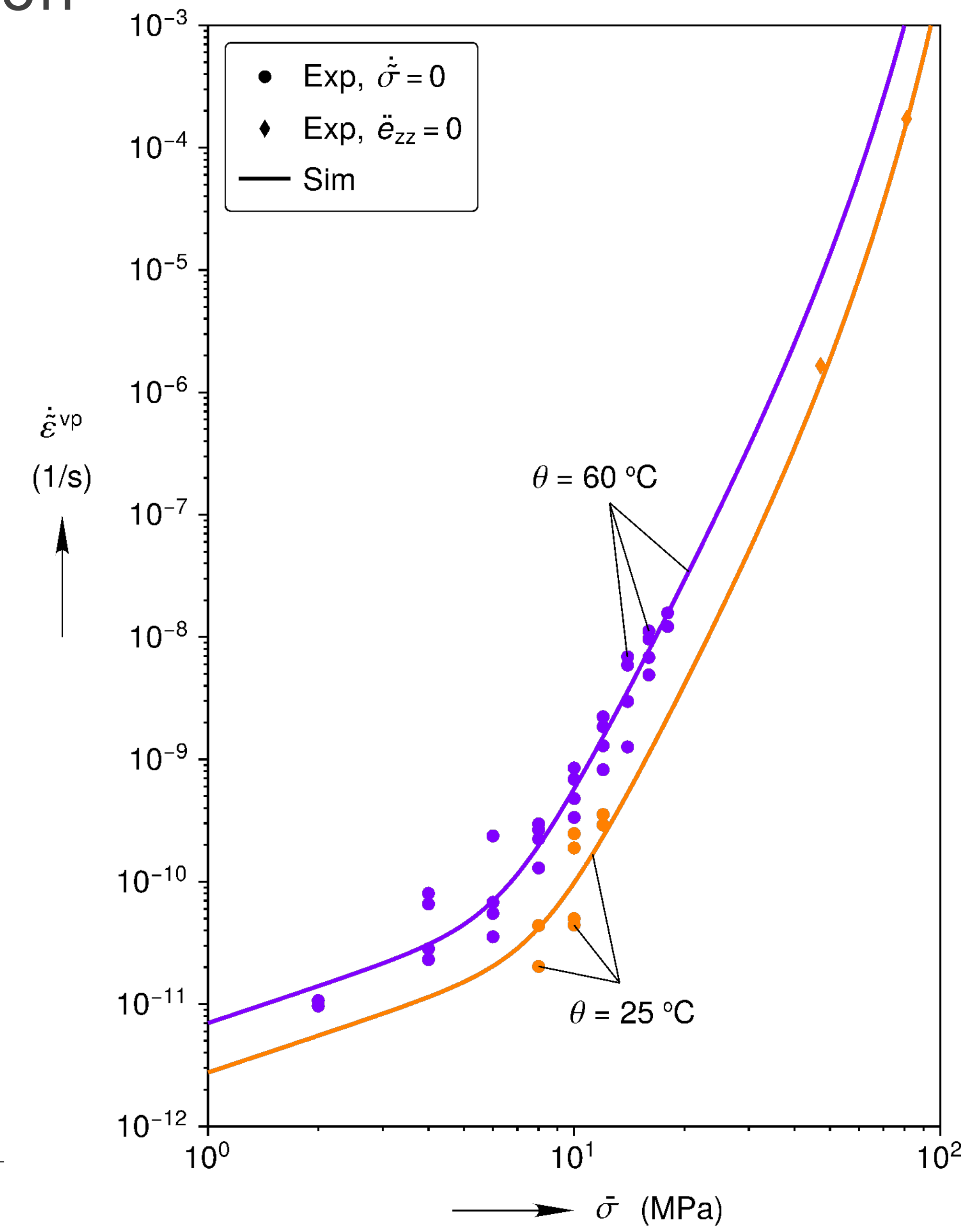

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Strain Rates While Hardening

Strain Rates
(proportional, monotonic, loading)

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$$\dot{\tilde{\varepsilon}}^{dg} = G_1 \exp\left(-\frac{G_2}{\theta}\right) \left[\sinh\left(\frac{\tilde{\sigma} - \tilde{b}}{y}\right)\right]^{G_3}$$

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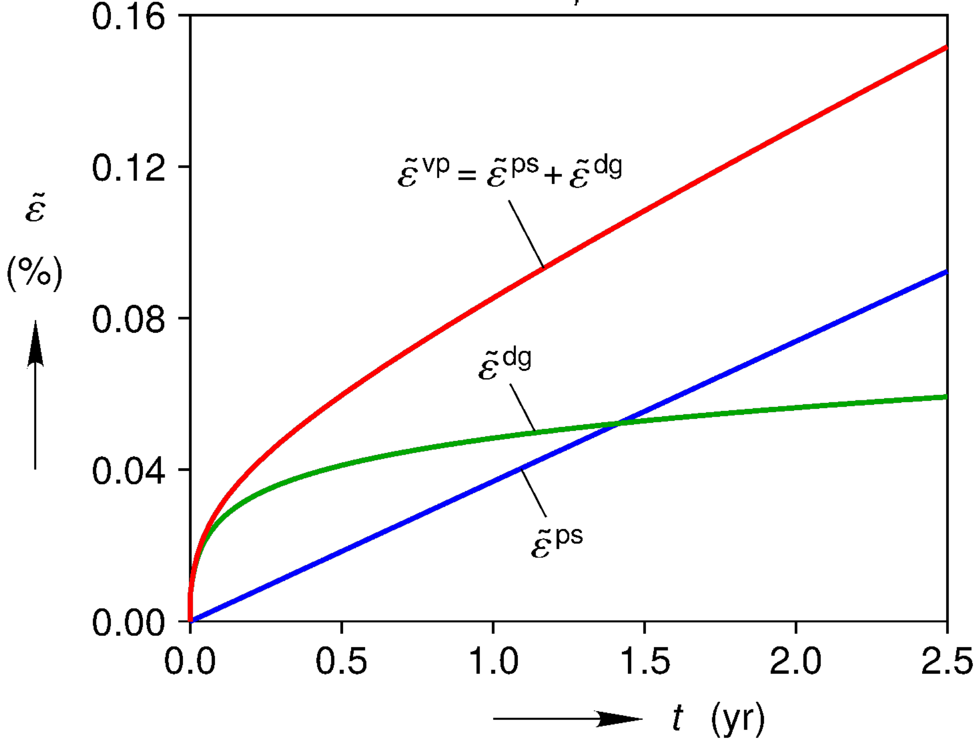
Low Constant Stress

$\tilde{\sigma}$ = 4 MPa, θ = 60°C



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Dislocation Glide Hardening

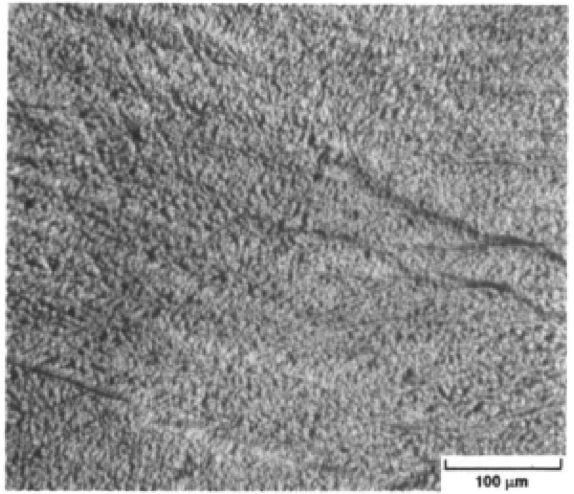
Equivalent Stress Decomposition
(proportional, monotonic, loading)

$$\tilde{\sigma} = \tilde{b} + \tilde{\sigma}^{\mathrm{dg}}$$

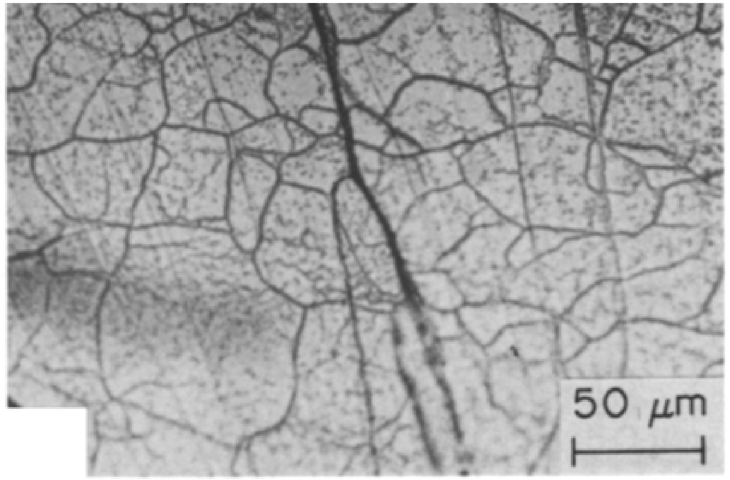
Drag Stress Contribution

$$\tilde{\sigma}^{\mathrm{dg}} = y \sinh^{-1}\left\{\left[\frac{\dot{\varepsilon}^{\mathrm{dg}}}{G_1 \exp\left(-G_2/\theta\right)}\right]^{1/G_3}\right\}$$

Uniform Dislocation Density



Non-Uniform Dislocation Density



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Carter, NL, Horseman, ST, Russell, JE, and Handin, J (1993). Rheology of rocksalt. Journal of Structural Geology. Vol 15. No 9-10. pp 1257-1271.

Dislocation Glide Hardening Saturation (Steady-State)

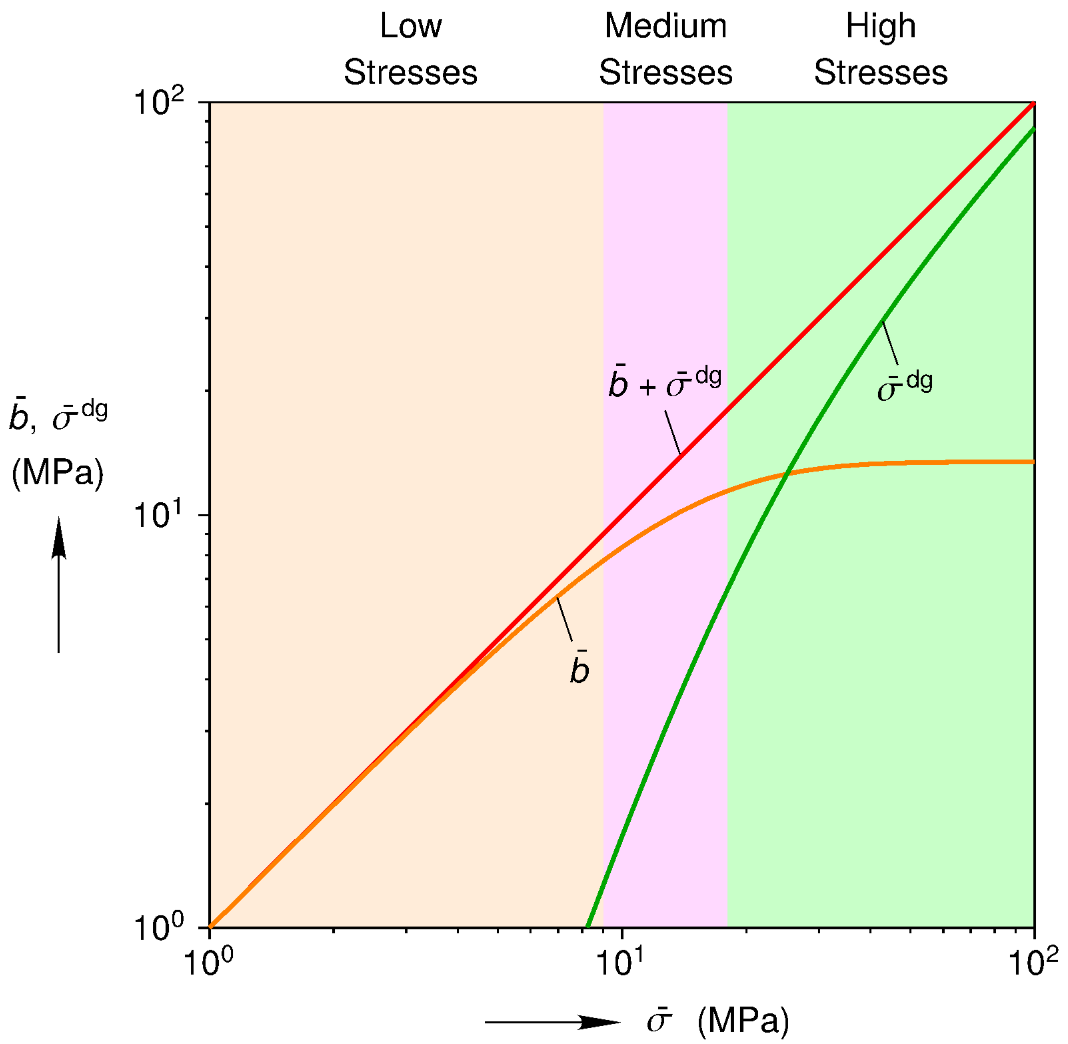
Equivalent Stress Decomposition
(proportional, monotonic, loading)

$$\bar{\sigma} = \bar{b} + \bar{\sigma}^{dg}$$

Drag Stress Contribution

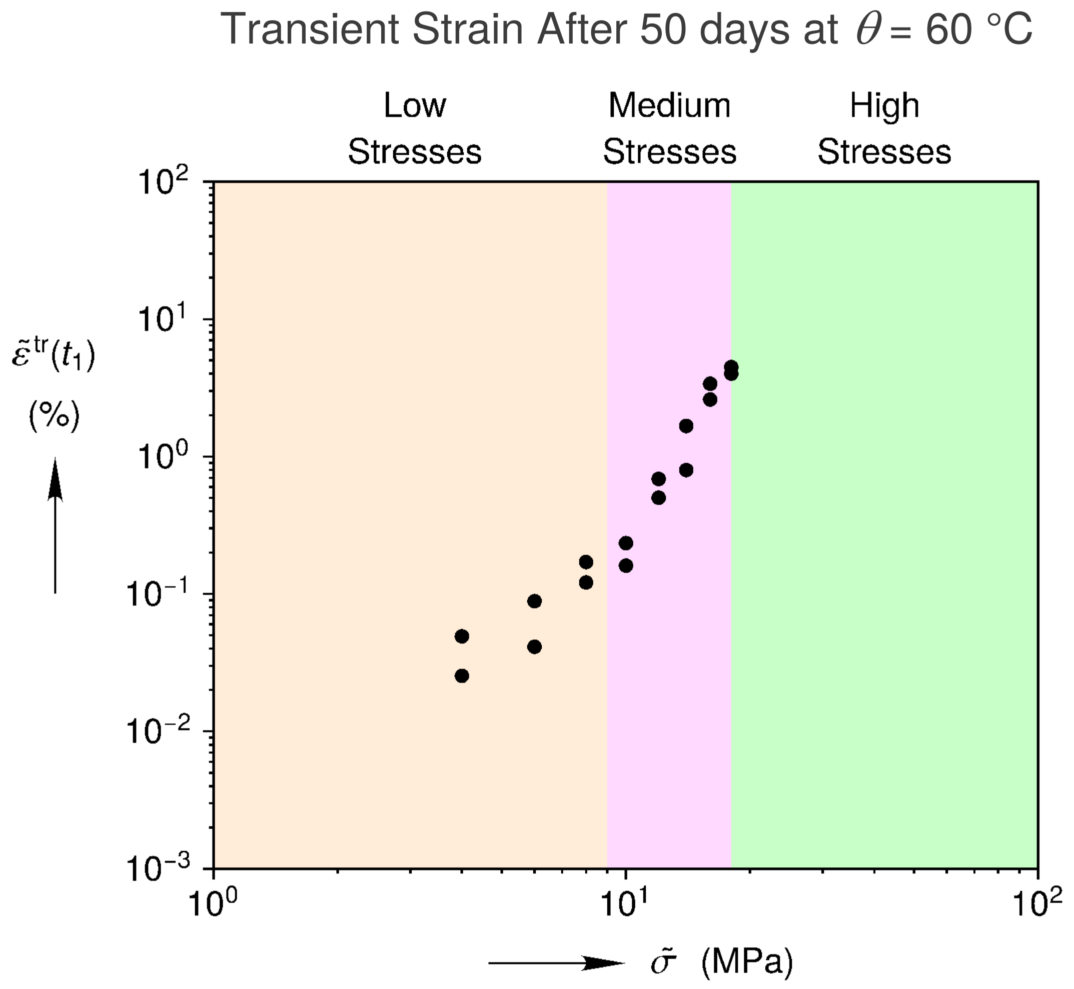
$$\bar{\sigma}^{dg} = \bar{y} \sinh^{-1} \left\{ \left[\frac{\dot{\bar{\varepsilon}}^{dg}}{G_1 \exp(-G_2/\theta)} \right]^{1/G_3} \right\}$$

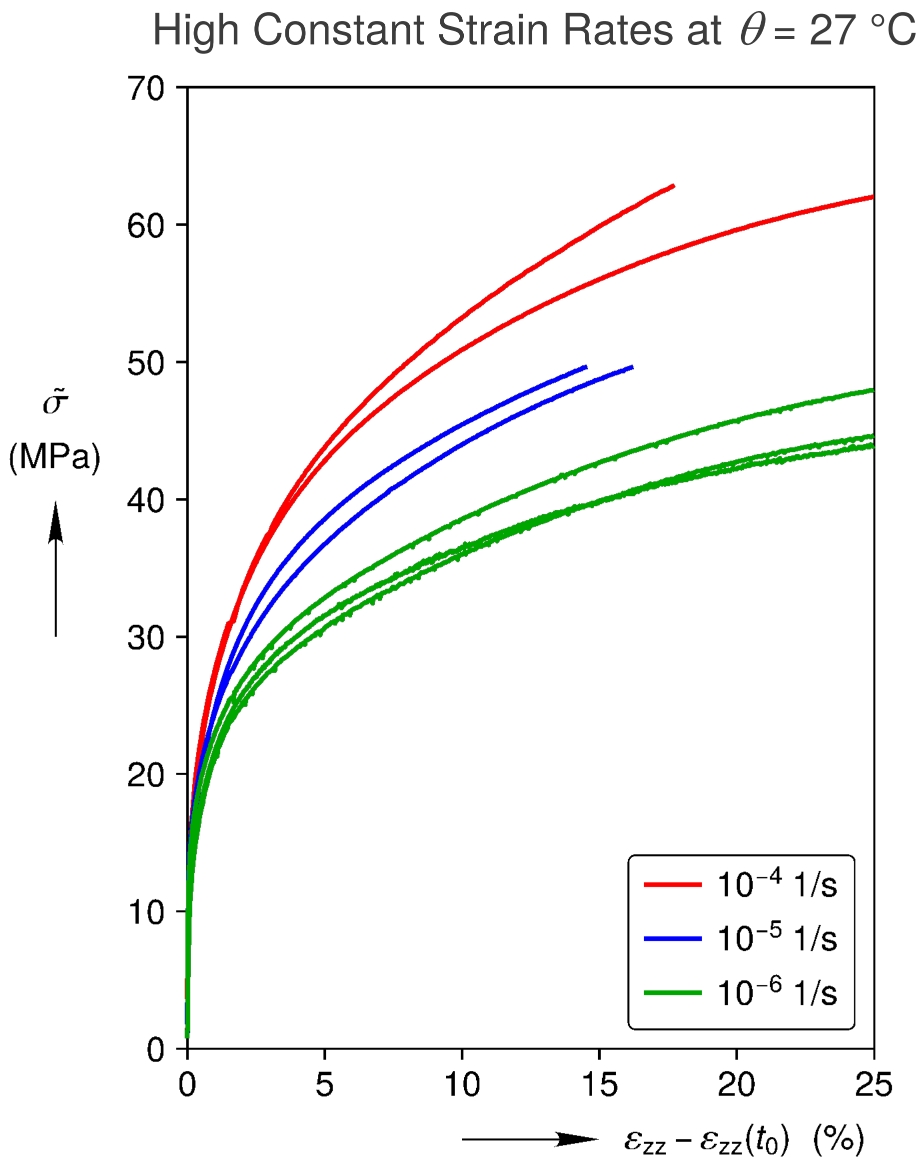
Contributions at Saturation



Hardening Calibrations

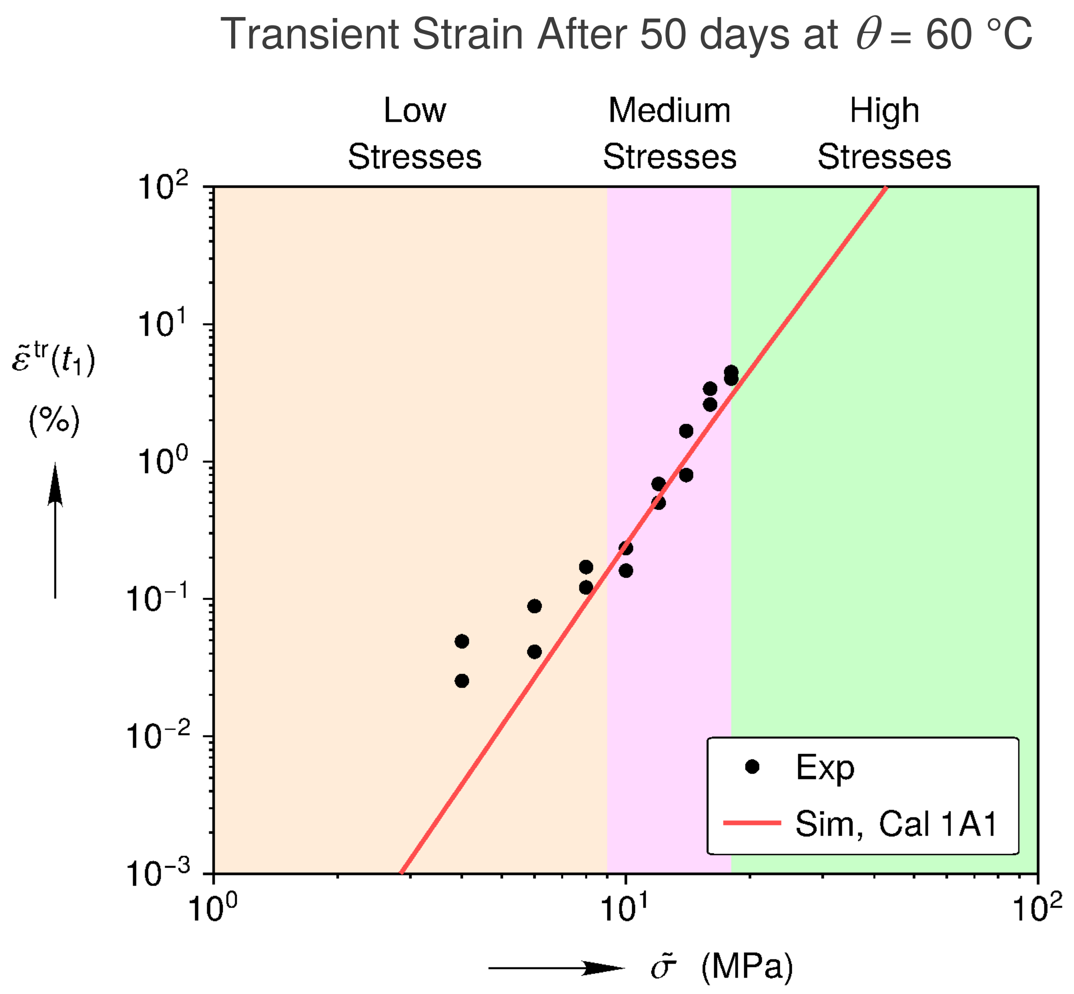
Selected Hardening Measurements on WIPP Salt

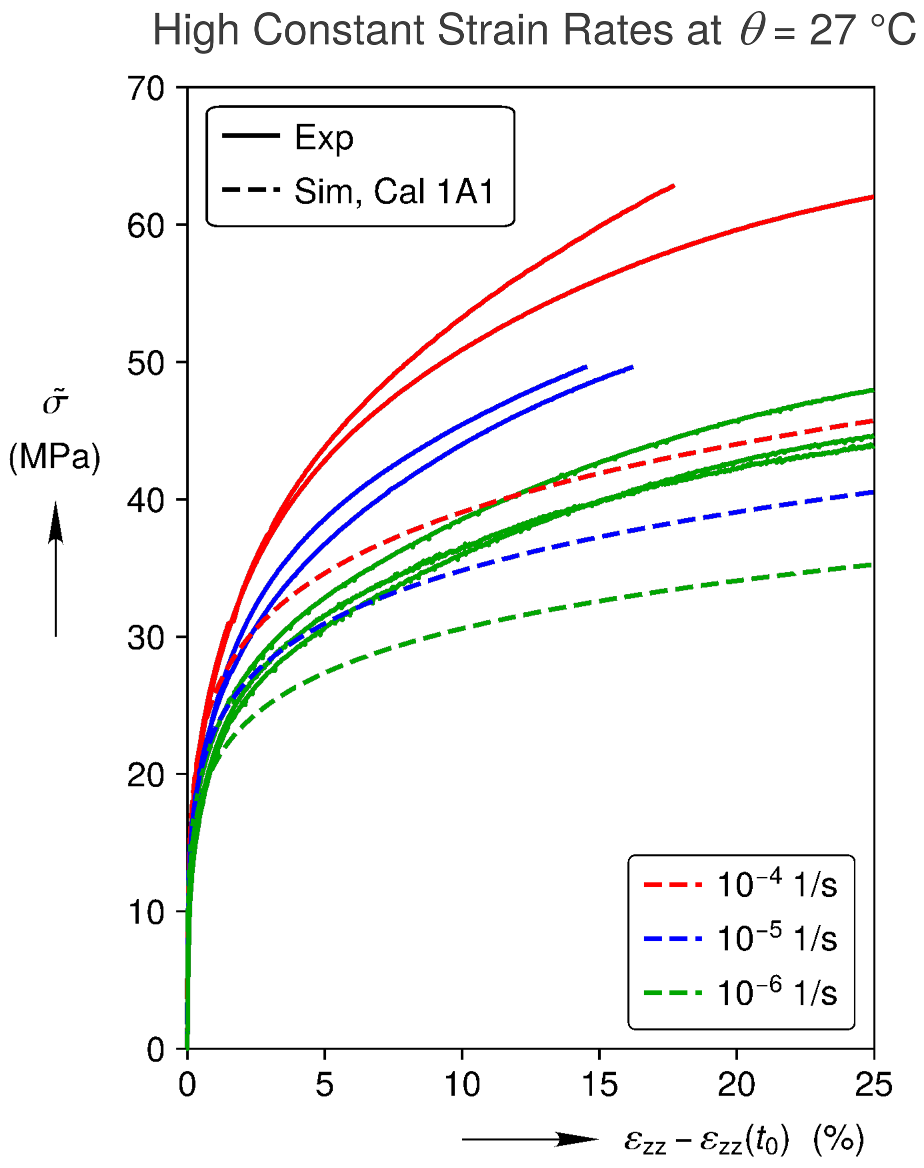




Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

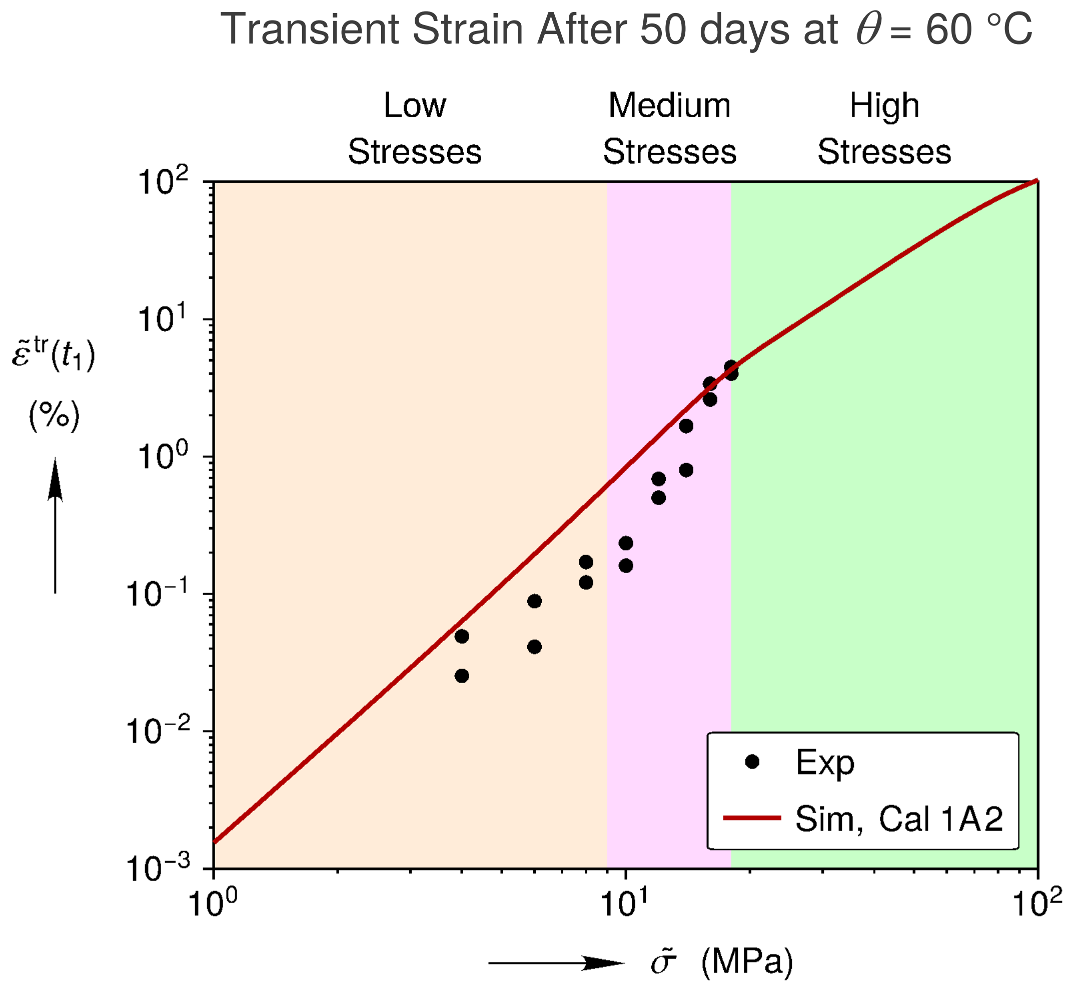
Calibration 1A1: Drag Stress Only

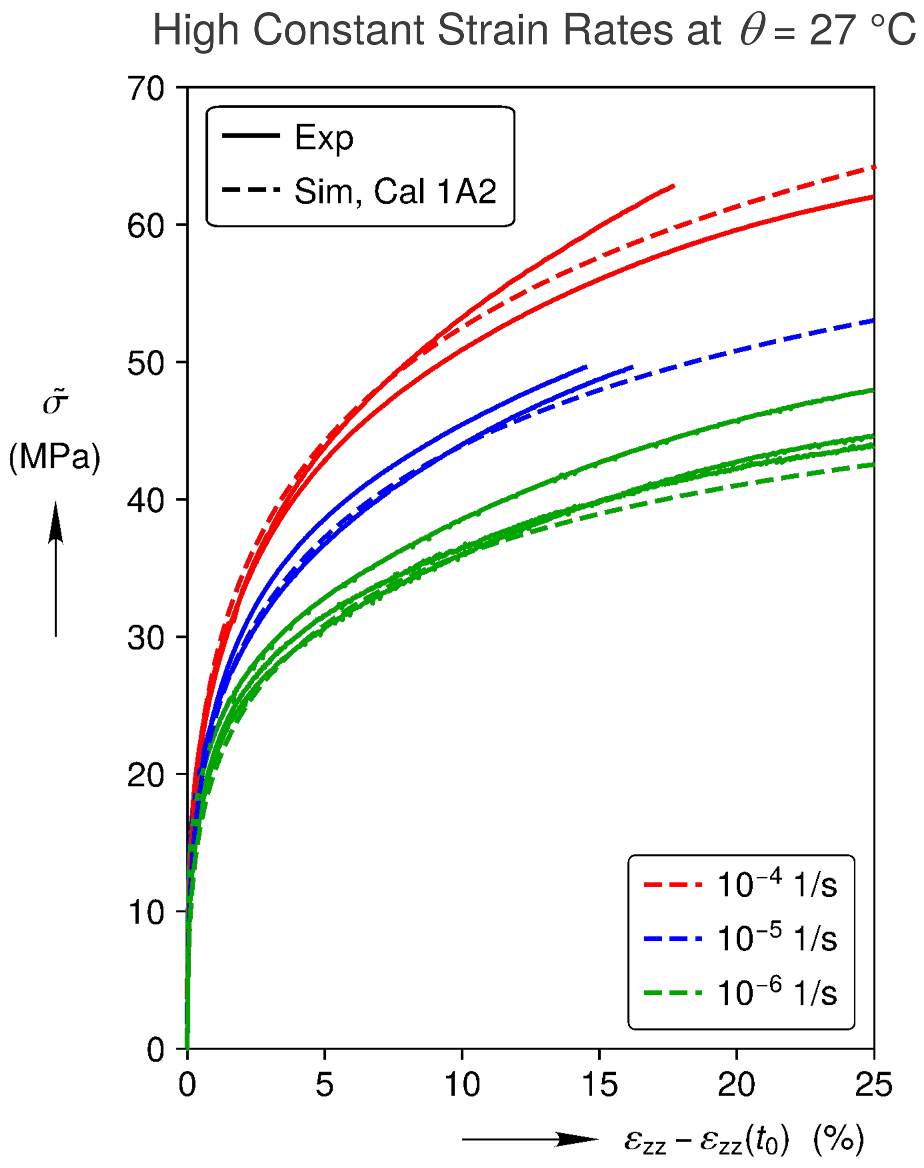




Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

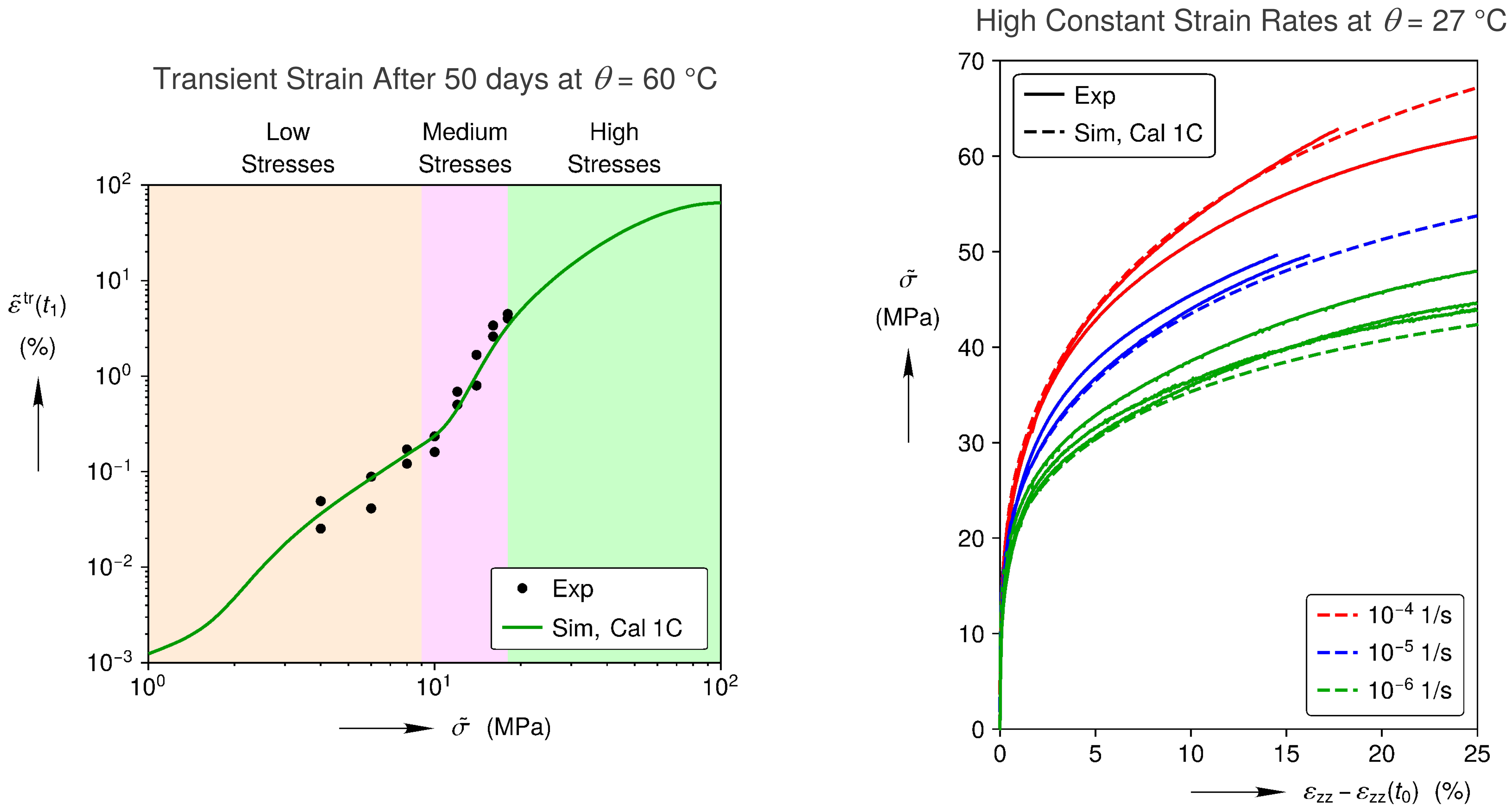
Calibration 1A2: Drag Stress Only





Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

Calibration 1C: Drag Stress and Back Stress

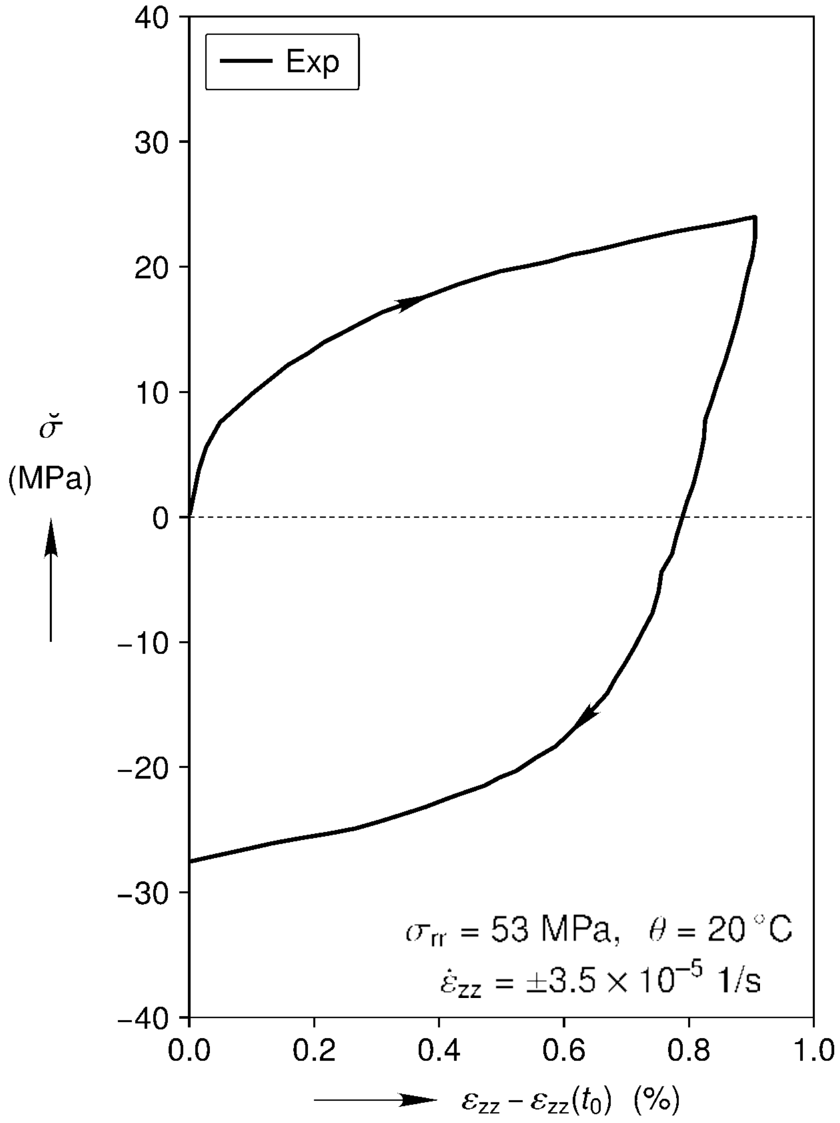


Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

Partial Validations

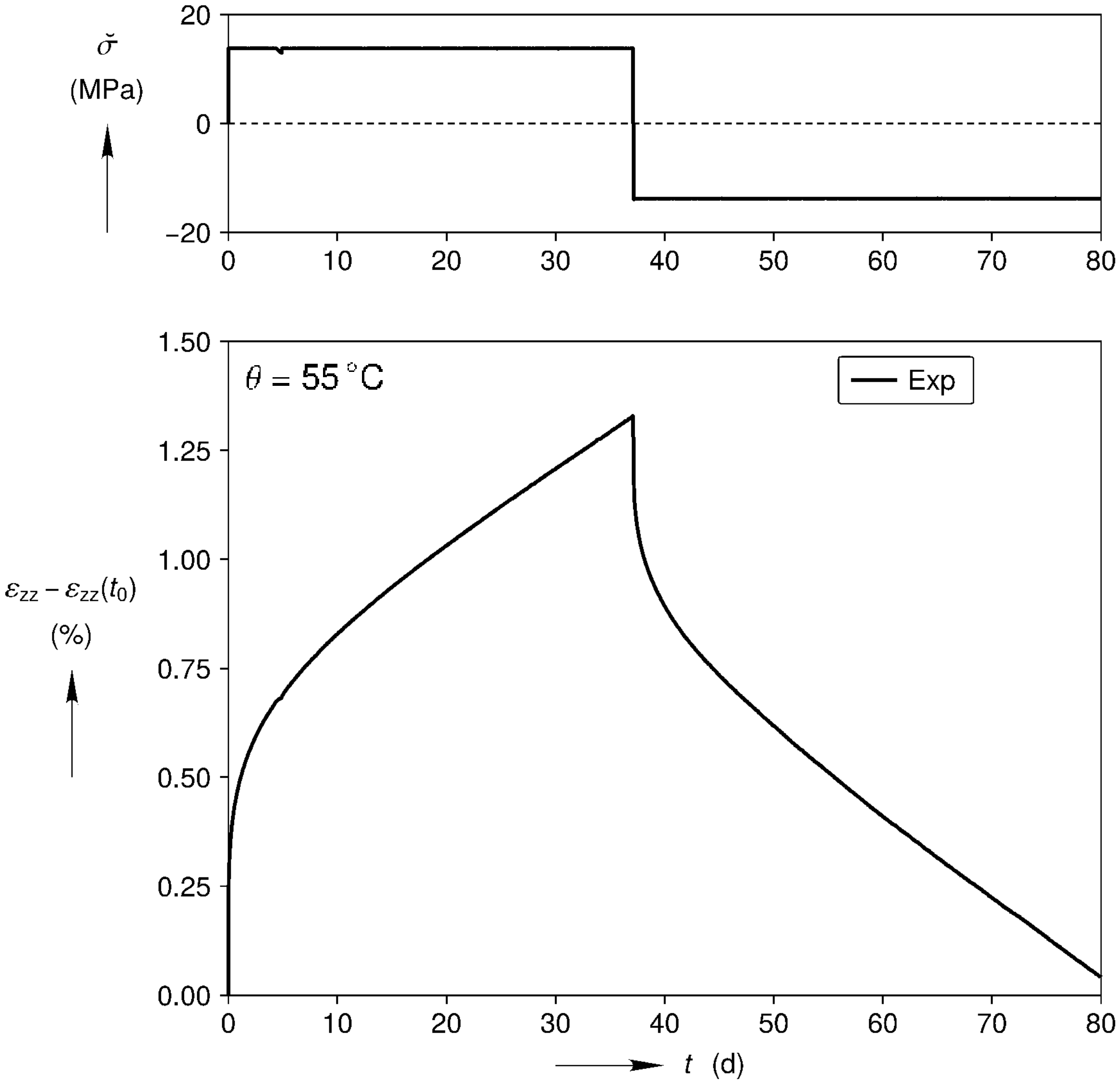
Re-hardening during Non-Monotonic Loading

Constant Strain Rate Test on Artificial Salt



Experimental measurements from: Aubertin et al. (1999)

Multi-Stage Constant Stress Test on Cayuta Salt



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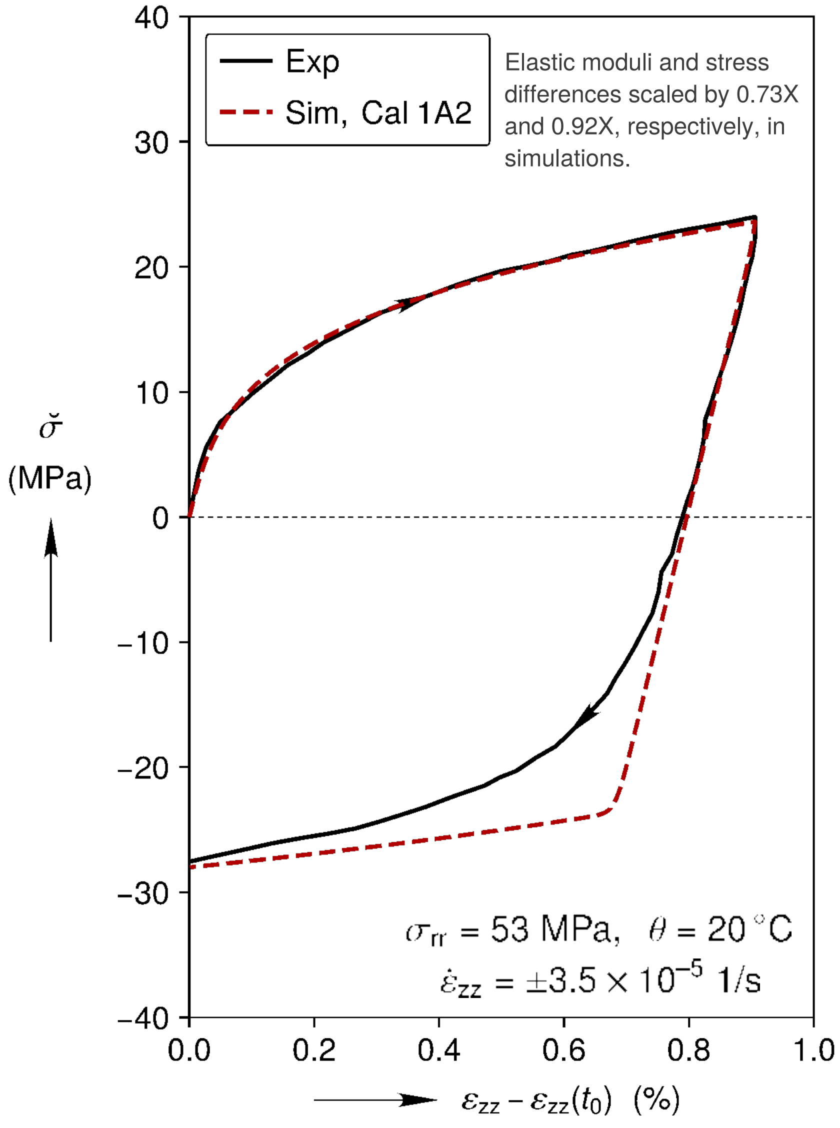

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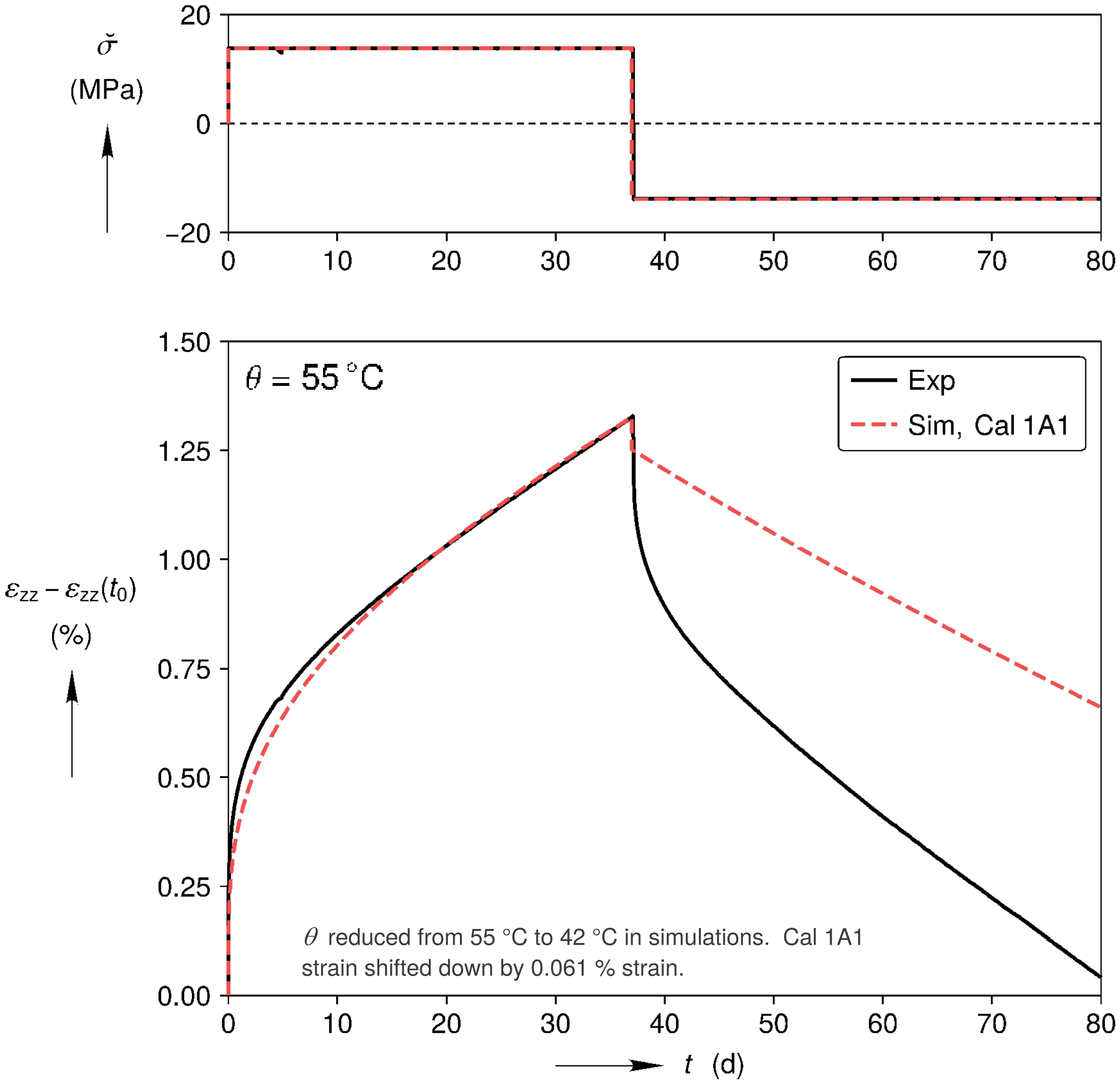

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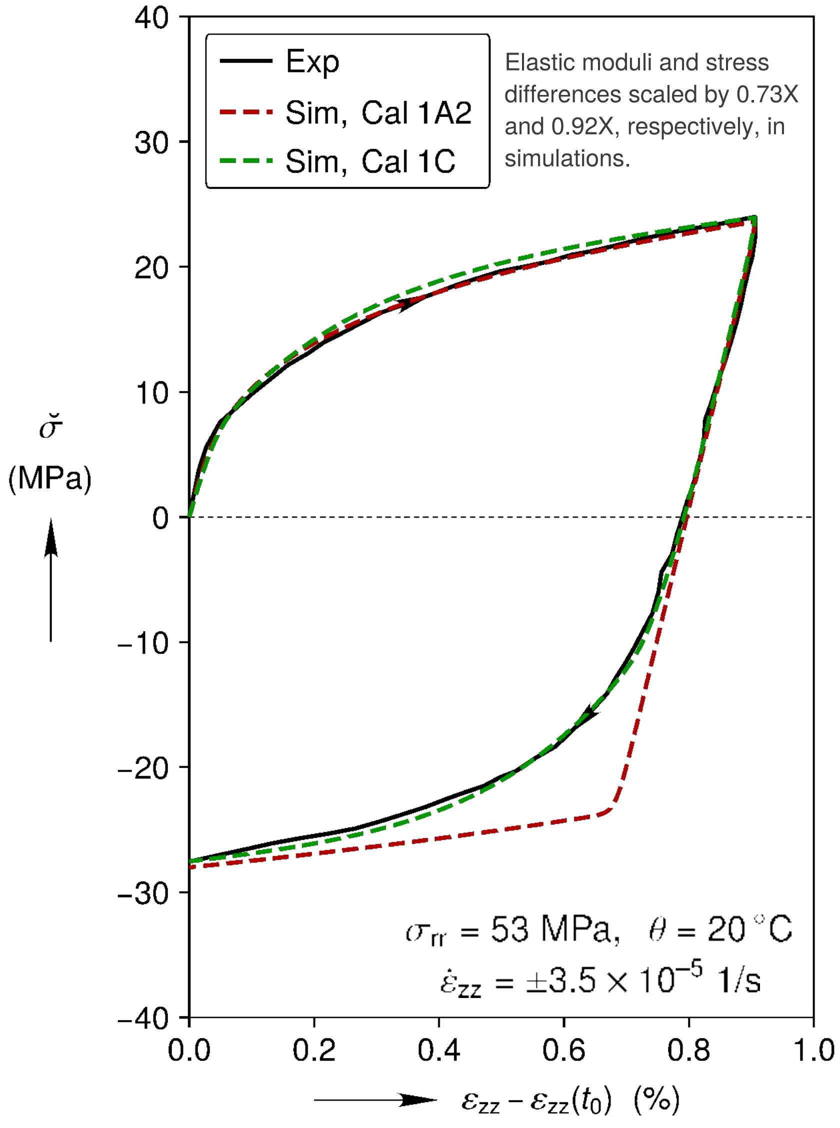

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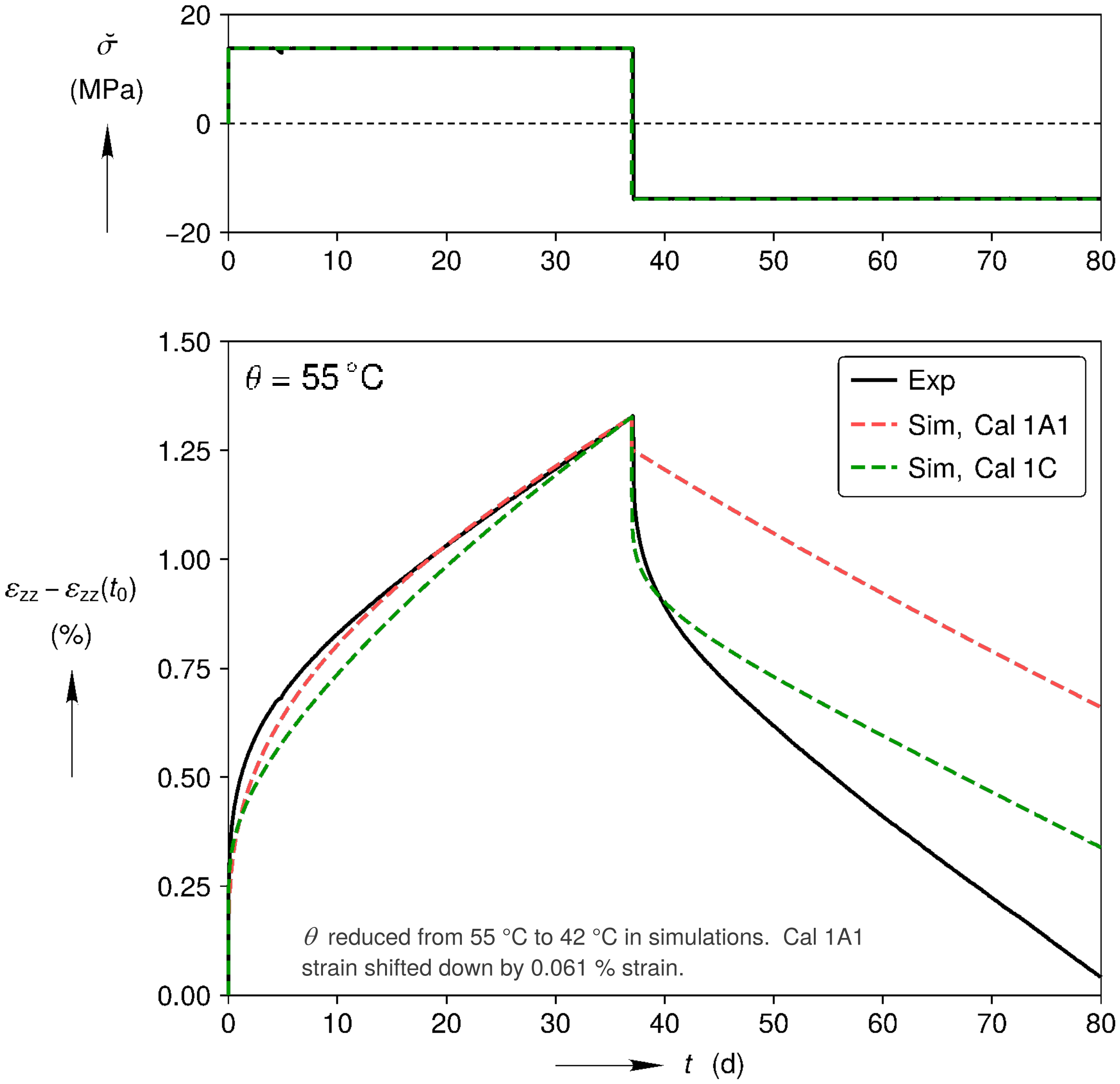


Experimental measurements from: Mellegard et al. (2007)

Summary & Future Work

Summary & Future Work

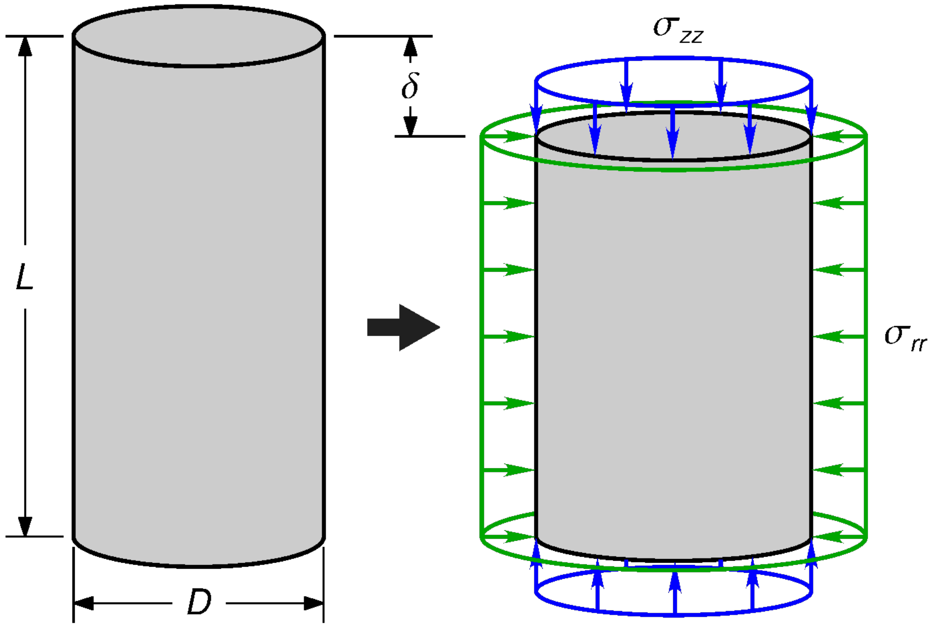
1. The new model is largely phenomenological, but key decisions were motived by micro-physical observations.
    1. Pressure solution and dislocation glide branches
    2. Drag stress hardening and back stress hardening
    3. Captures rock salt's viscoplastic behavior over a wide range of strain rates (10^{-12} to 10^{-4} 1/s)
    4. Predicts re-hardening behavior after non-monotonic loading
2. Future work
    1. Polish numerical implementation
    2. Simulate underground structures
    3. Add damage and healing

Extra Slides

Outline

1. Background
2. Model Overview
3. Hardening Calibrations
4. Partial Validation
5. Summary

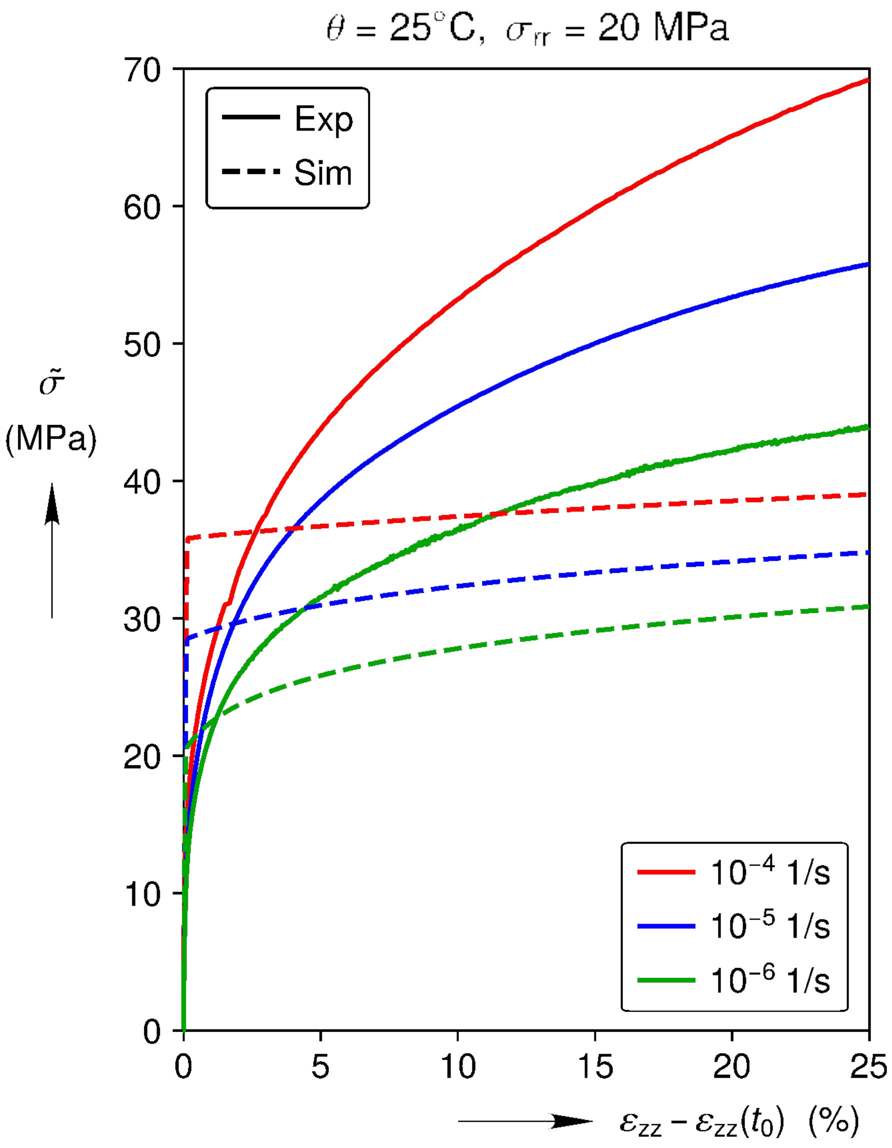
Damage-Free, High Strain Rate, Munson-Dawson Predictions



$$\frac{L}{D} = 2$$

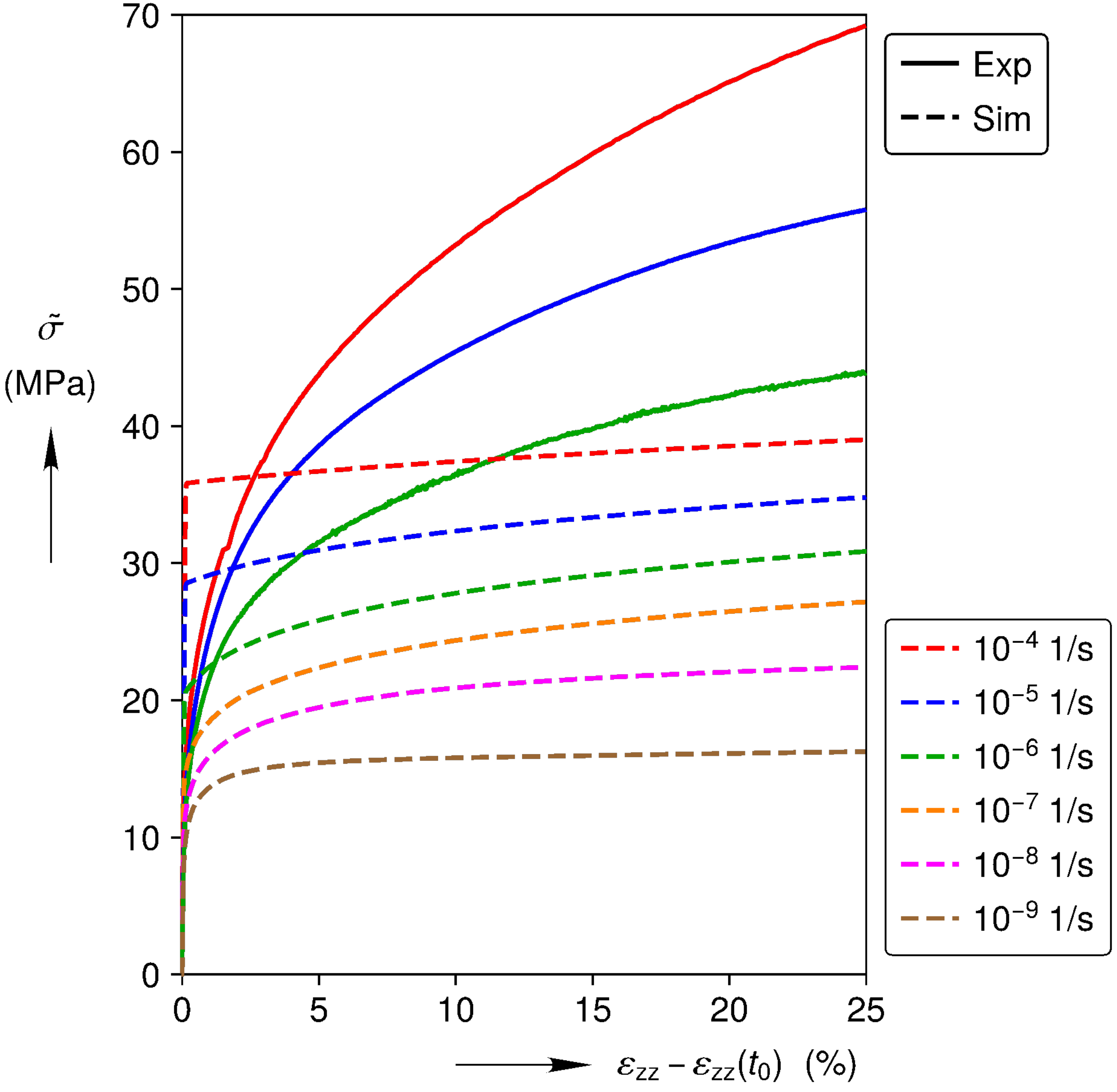
$$\varepsilon_{zz} = \ln\left(1 + \frac{\delta}{L}\right)$$

$$\tilde{\sigma} = |\sigma_{zz} - \sigma_{rr}|$$

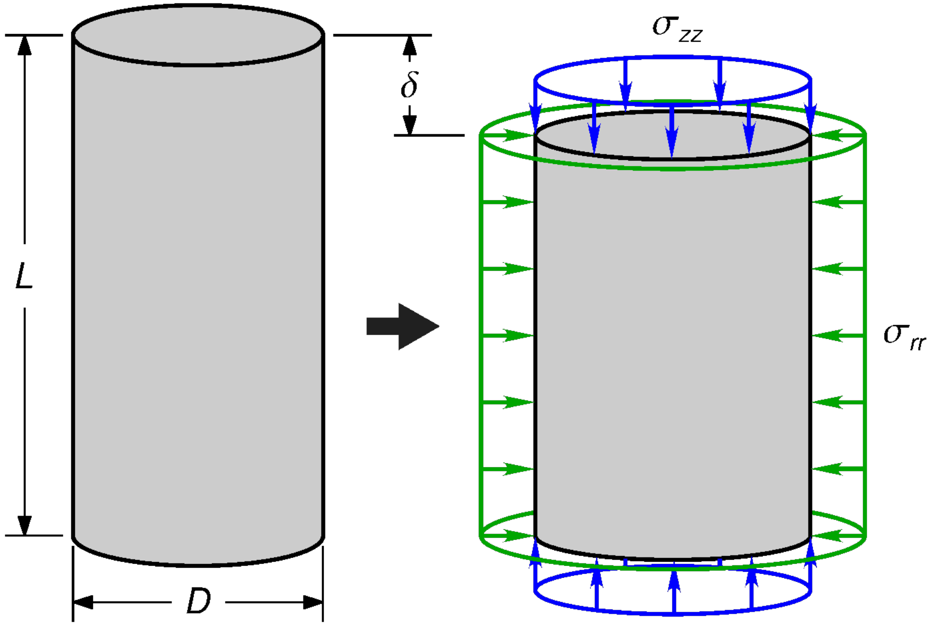


Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

Munson-Dawson Model Constant Strain Rate Predictions



Damaged, High Strain Rate, Behavior



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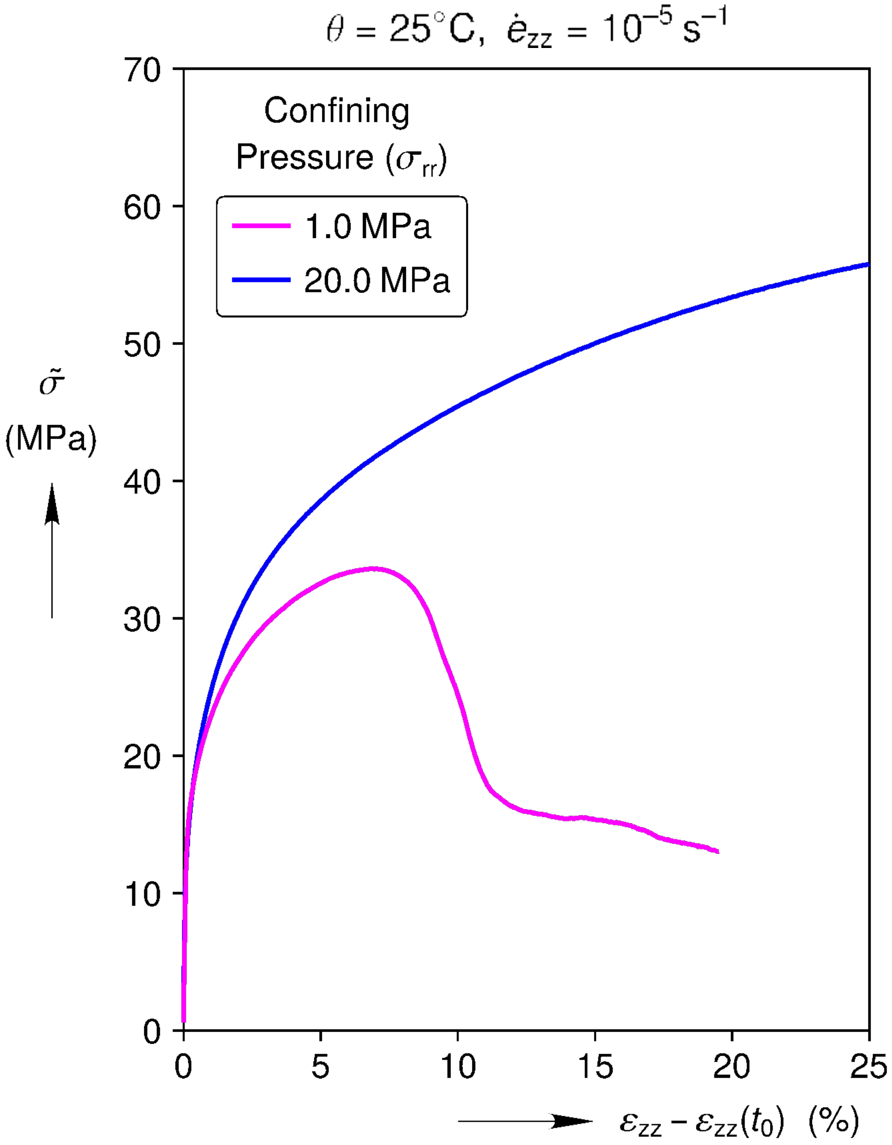
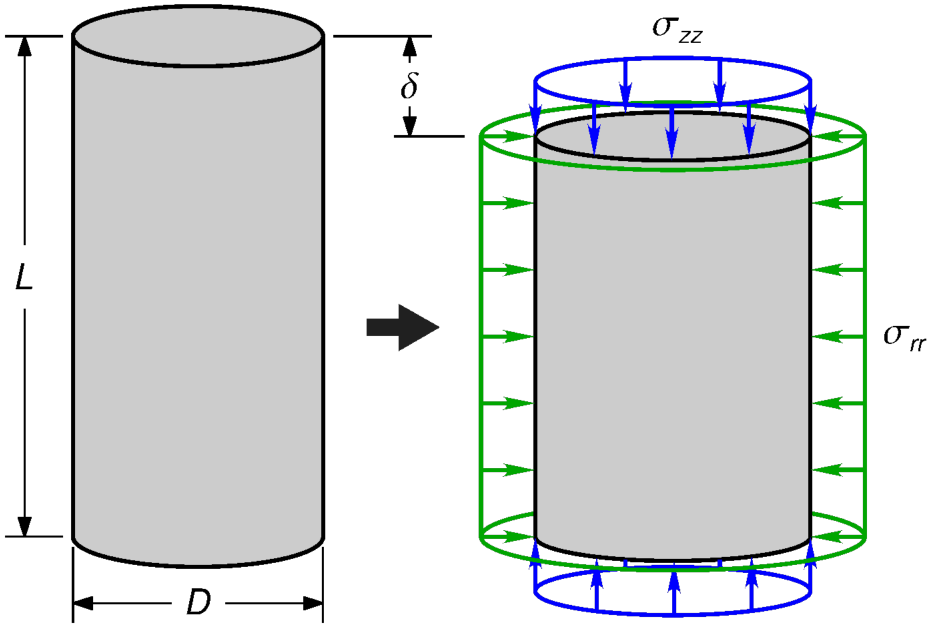


Experimental measurements from: Salzer et al. (2015) and Düsterloh et al. (2015).

Damaged, High Strain Rate, Behavior



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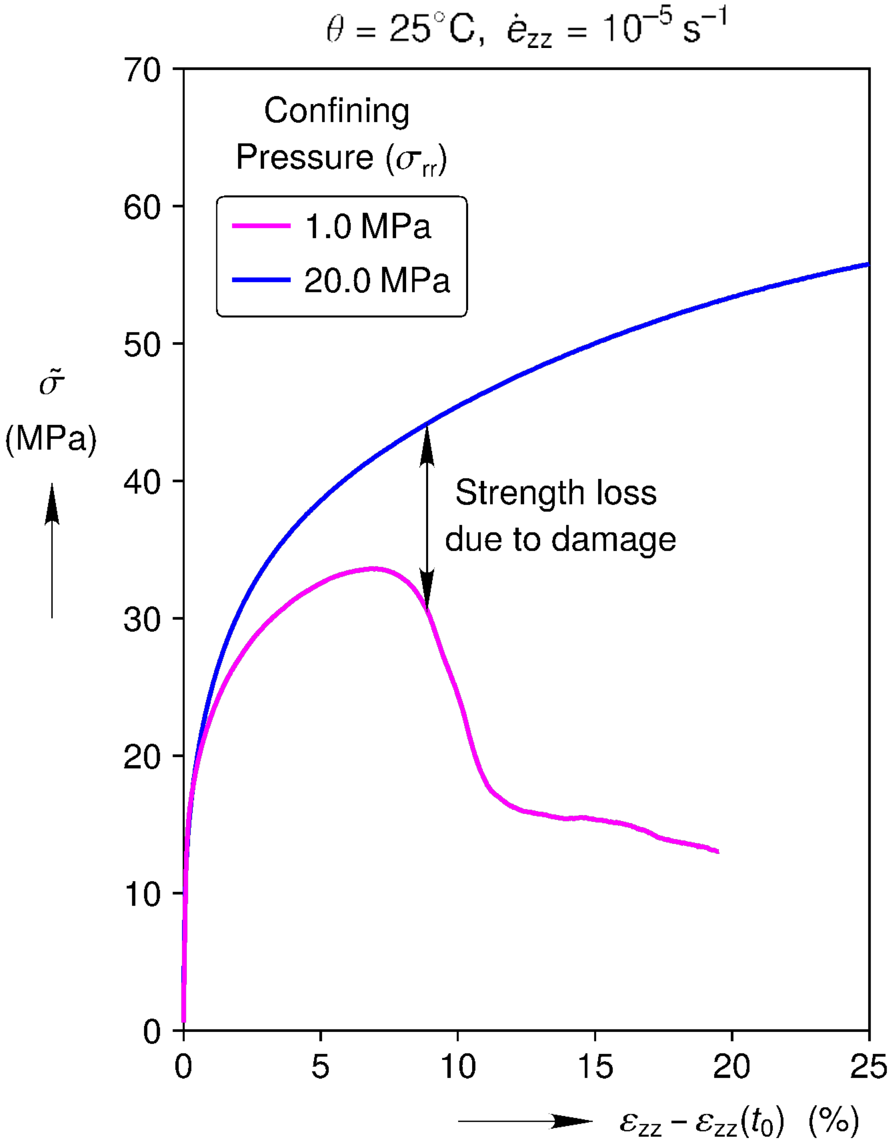

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Constant Strain Rate Tests on Artificial Salt

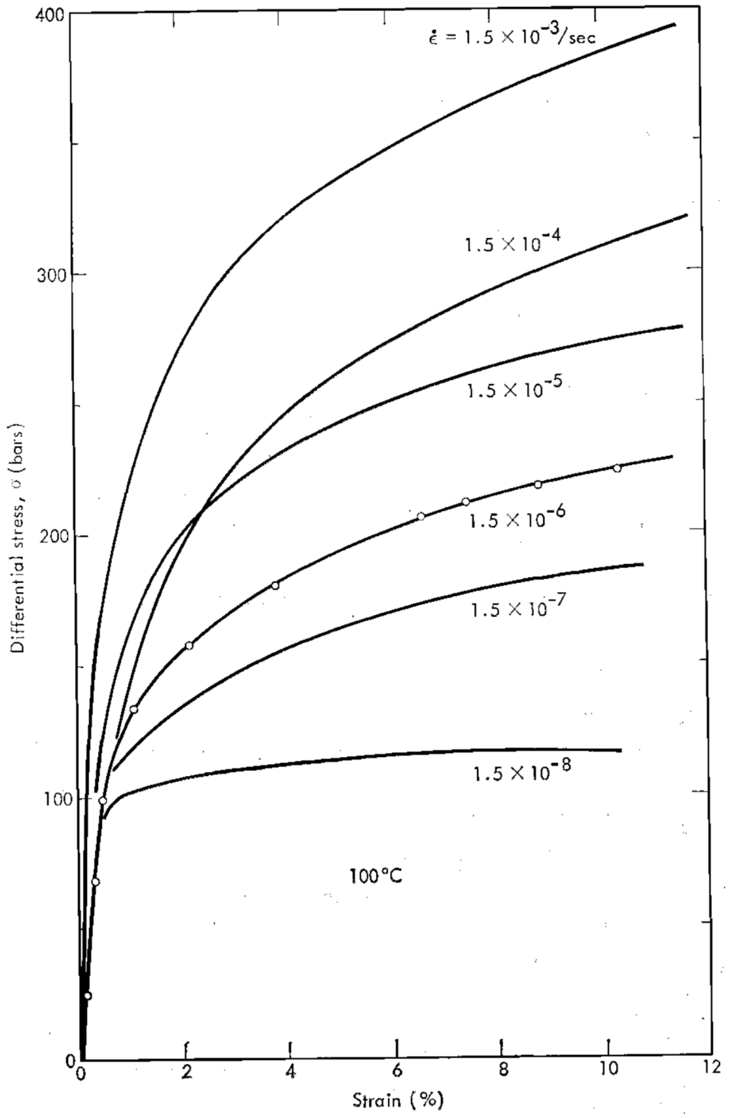
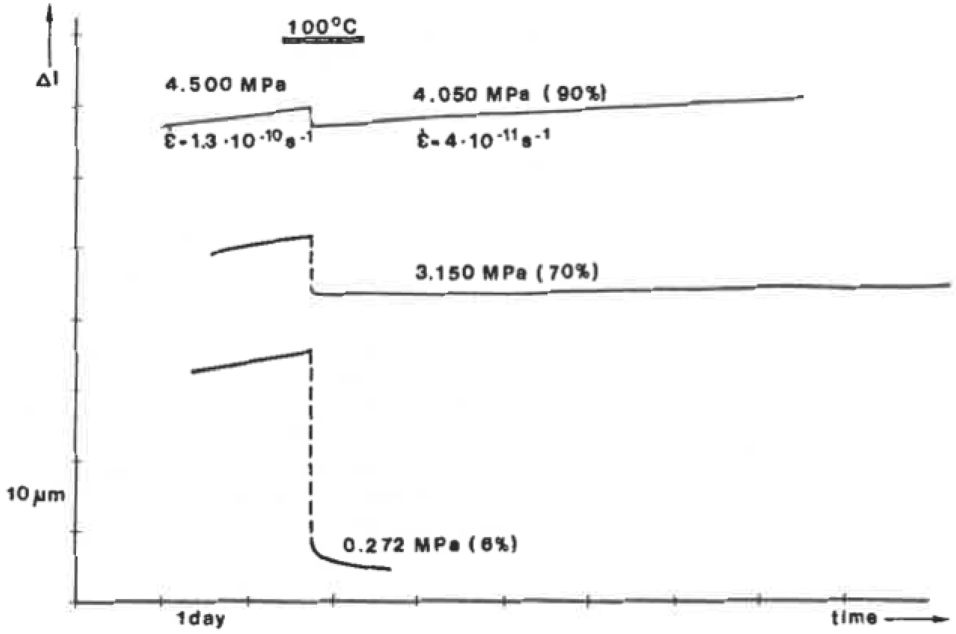


Fig. 1. Differential stress-strain curves for polycrystalline halite extended at 2 kb, $\dot{\epsilon} = 1.5 \times 10^{-3}$ to 1.5×10^{-8} sec^{-1}, and 100°C.

Heard, H. (1972). Steady-state flow in polycrystalline halite at pressure of 2 kilobars. *Flow and fracture of rocks.* Vol 16. pp 191-209.

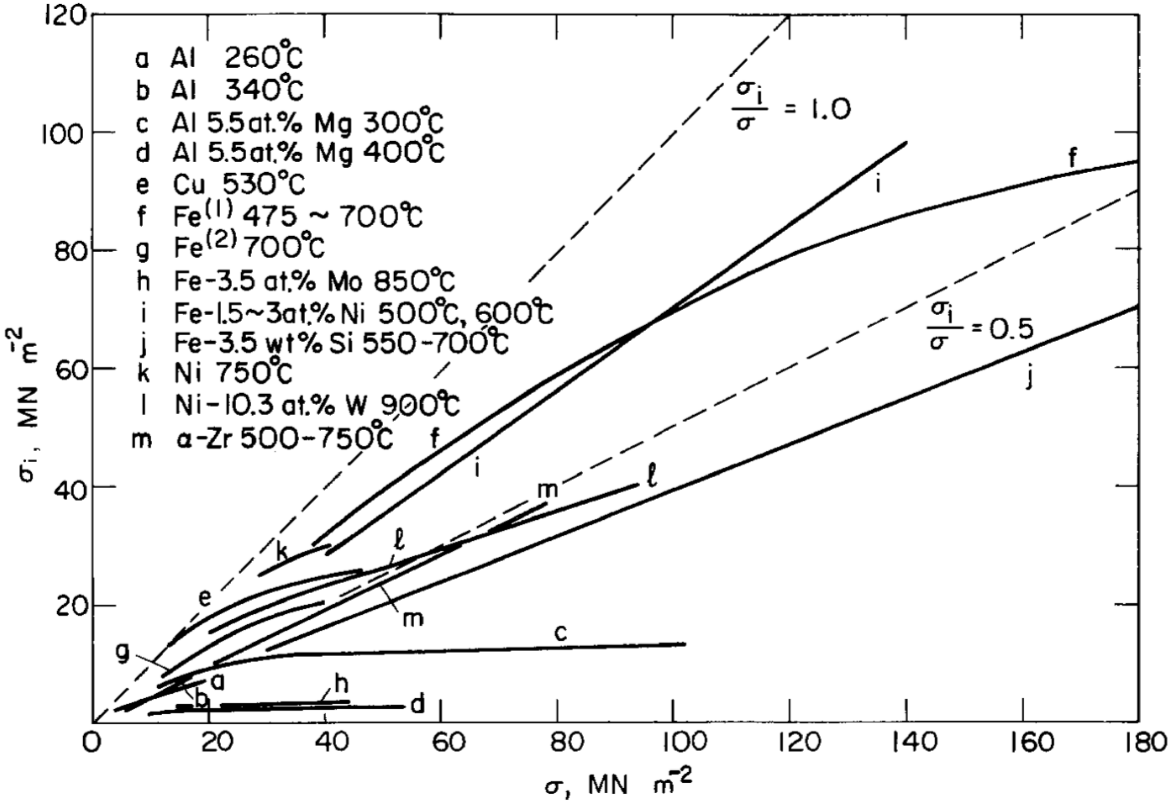
Back Stress Measurements

Creep Responses due to Small Stress Changes Asse Rock Salt



Hunsche, U. 1988. Measurement of creep in rock salt at small strain rates. Proceedings of the 2nd Conference on the Mechanical Behavior of Salt. Pg. 187-196

Back Stress Measurements on Single Phase Metals



Takeuchi, S. and Argon, A. (1976). "Steady-state creep of single-phase crystalline matter at high temperature". In: Journal of Materials Science 11.8, pp. 1542–1566.

Dislocation Glide Strain Rate (proportional loading)

$$\dot{\varepsilon}^{dg} = G_1 \exp\left(-\frac{G_2}{\theta}\right)\left[\sinh\left(\frac{\left|\breve{\sigma}-\breve{b}\right|}{y}\right)\right]^{G_3} \operatorname{sign}\left(\breve{\sigma}-\breve{b}\right)$$

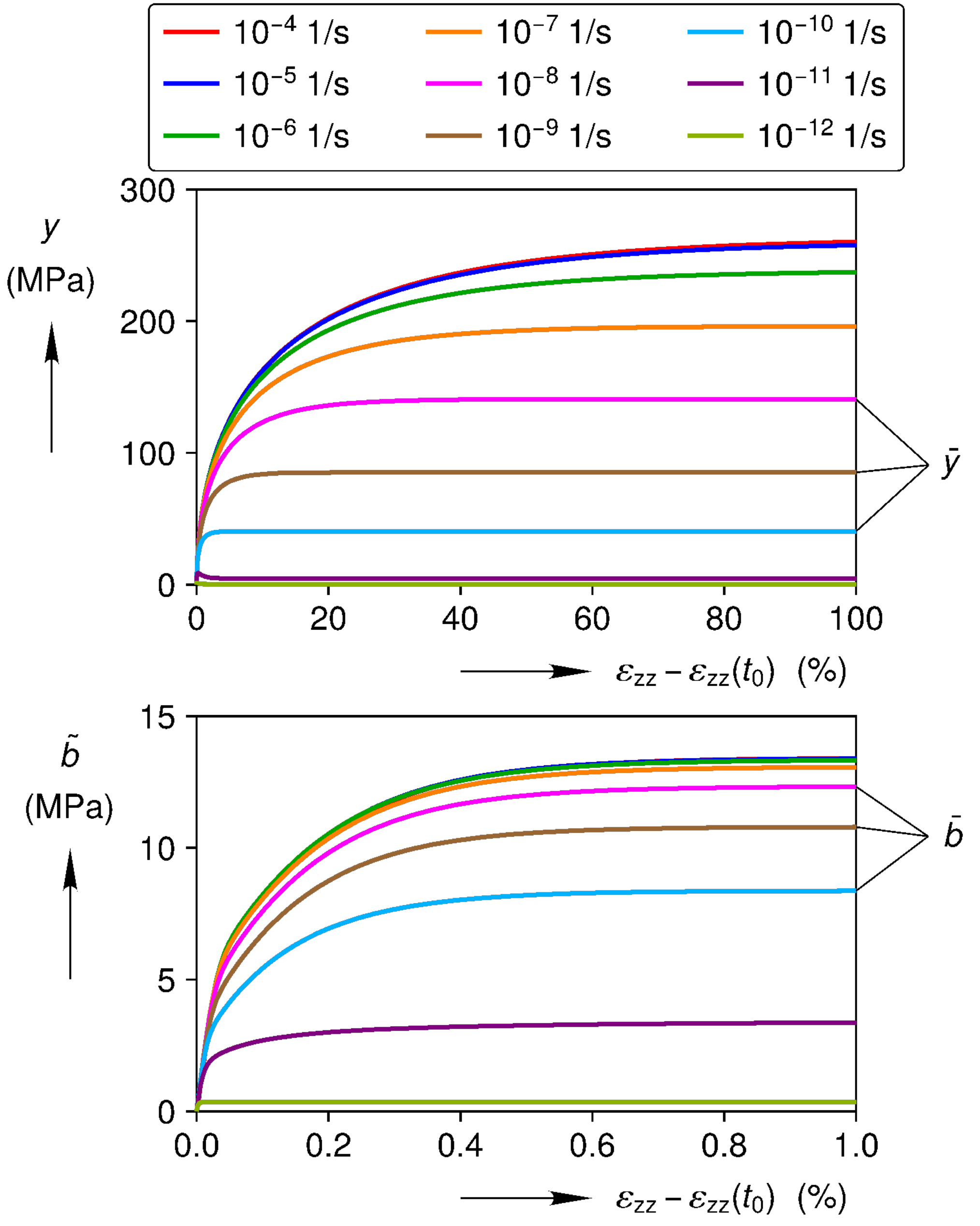
Dislocation Glide Hardening

Drag Stress Evolution Equation

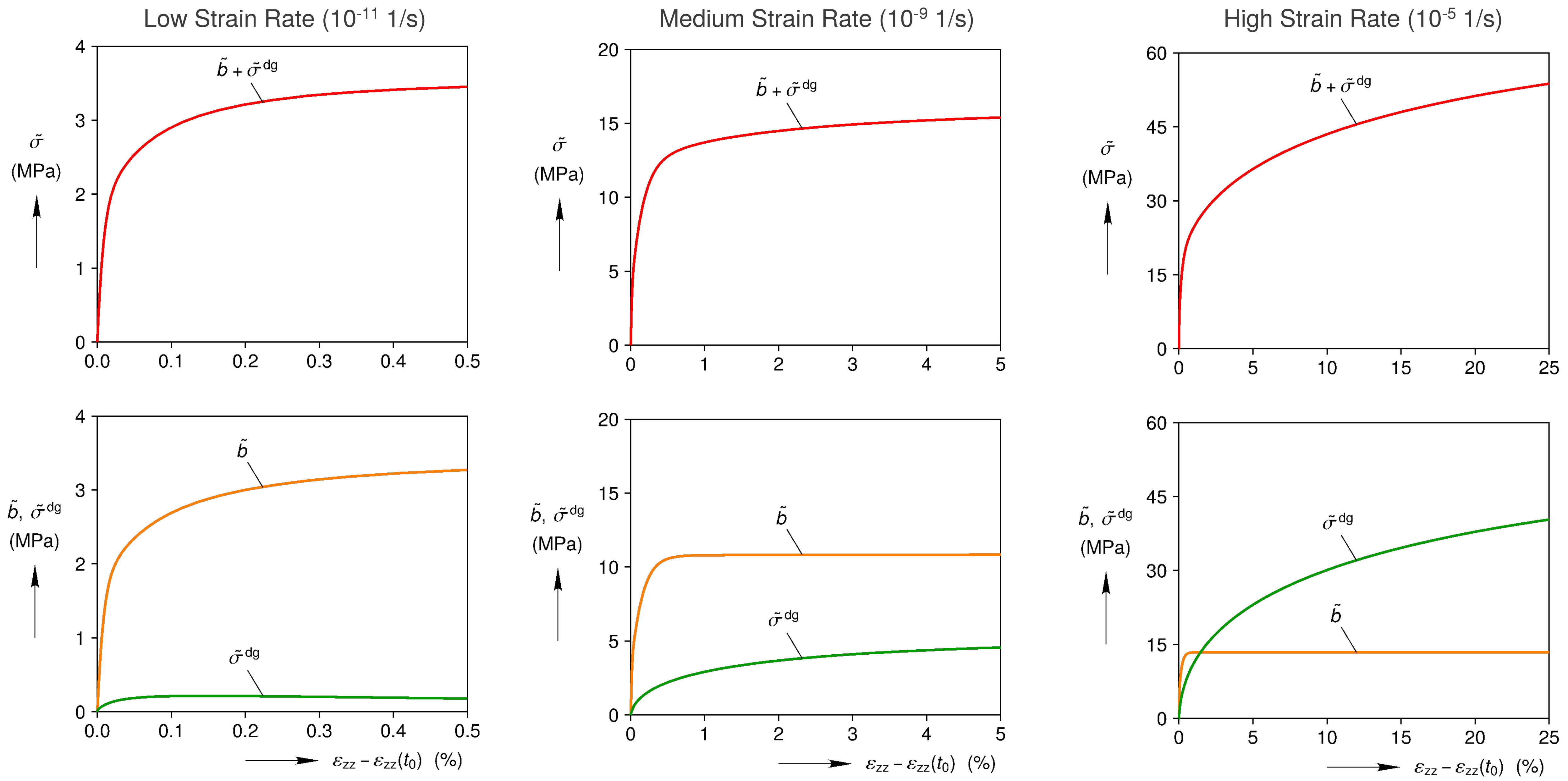
$$\dot{y} = Y_1 \left(\frac{Y_1}{y}\right)^{Y_2} \left(1 - \frac{y}{\bar{y}}\right) \dot{\tilde{\varepsilon}}^{dg}$$

Back Stress Evolution Equation
(proportional, monotonic, loading)

$$\dot{\tilde{b}} = B_1 \left(1 - \frac{\tilde{b}}{\bar{b}}\right) \dot{\tilde{\varepsilon}}^{dg}$$

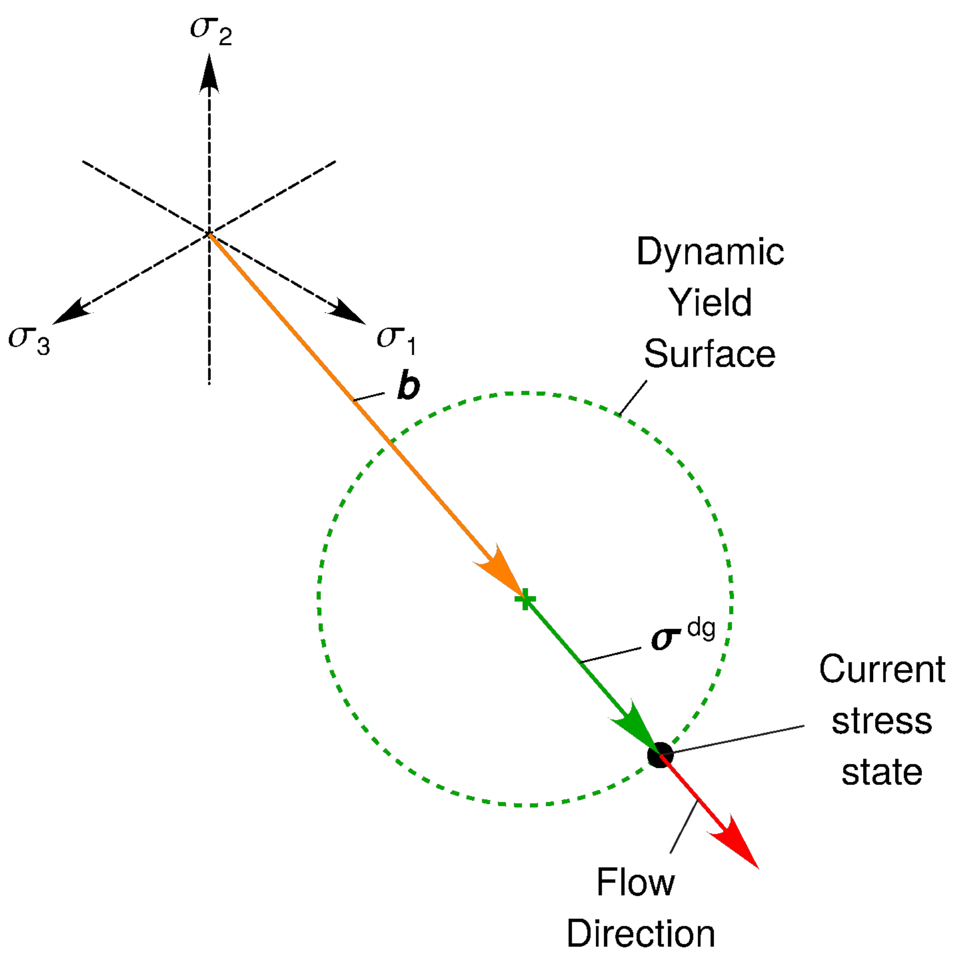


Constant Strain Rate Behavior



Dislocation Glide Hardening

Deviatoric Plane



Dislocation Glide Stress

$$\boldsymbol{\sigma}^{dg} = \boldsymbol{\sigma}^{dev} - \boldsymbol{b}$$

$$\tilde{\sigma}^{dg} = \sqrt{\frac{3}{2}\boldsymbol{\sigma}^{dg} : \boldsymbol{\sigma}^{dg}}$$

Flow Rule

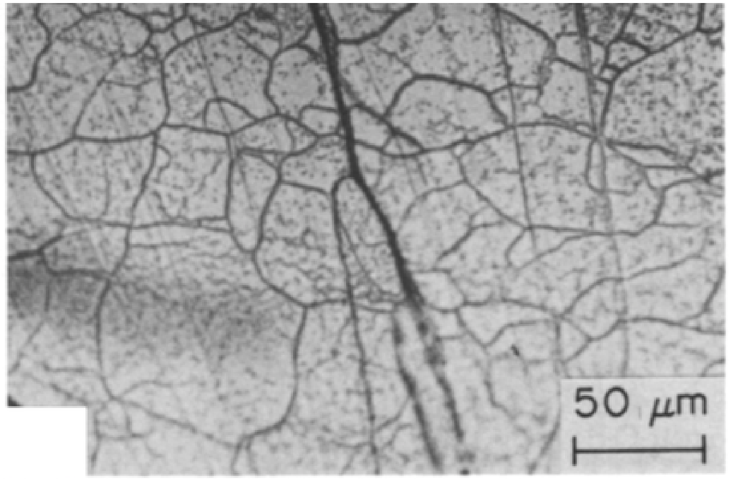
$$\dot{\boldsymbol{\varepsilon}}^{dg} = \dot{\tilde{\varepsilon}}^{dg} \frac{\partial \tilde{\sigma}^{dg}}{\partial \boldsymbol{\sigma}}$$

Dislocation Glide Strain Rate

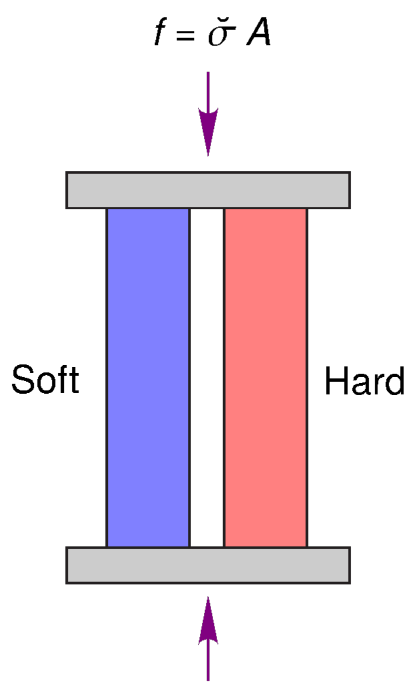
$$\dot{\tilde{\varepsilon}}^{dg} = G_1 \exp\left(-\frac{G_2}{\theta}\right) \left[\sinh\left(\frac{\tilde{\sigma}^{dg}}{y}\right)\right]^{G_3}$$

A “Gedankenexperiment”

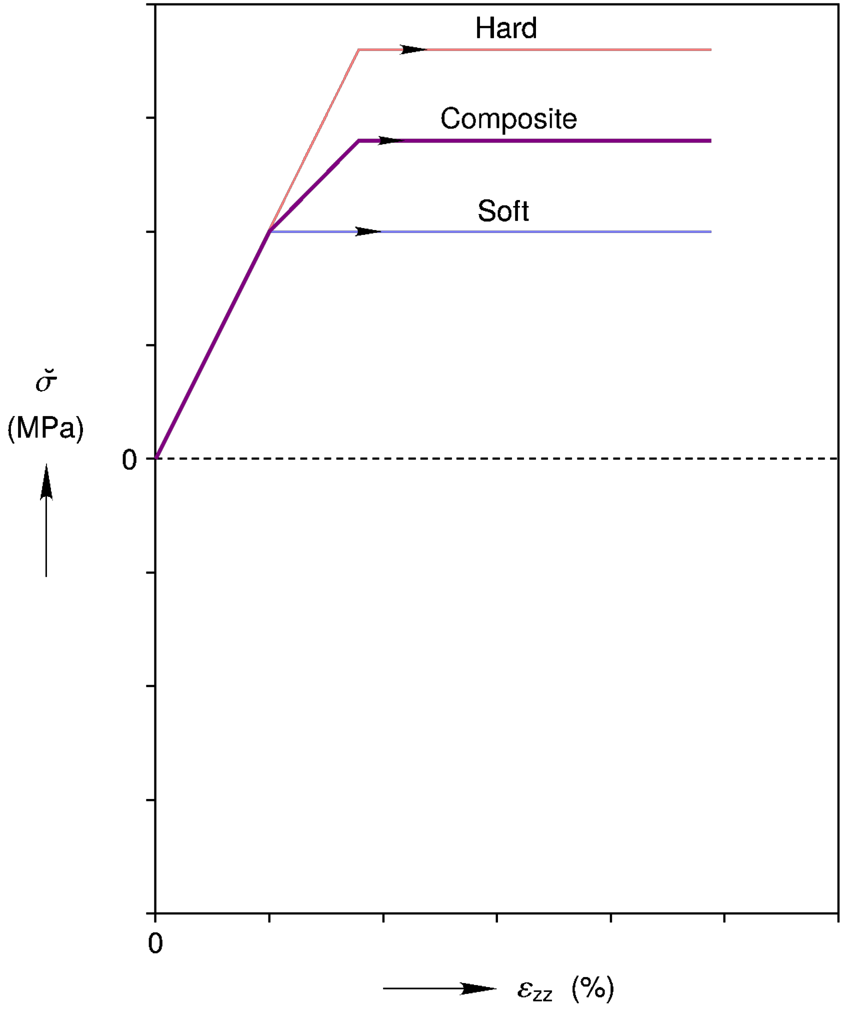
Subgrains



Schematic



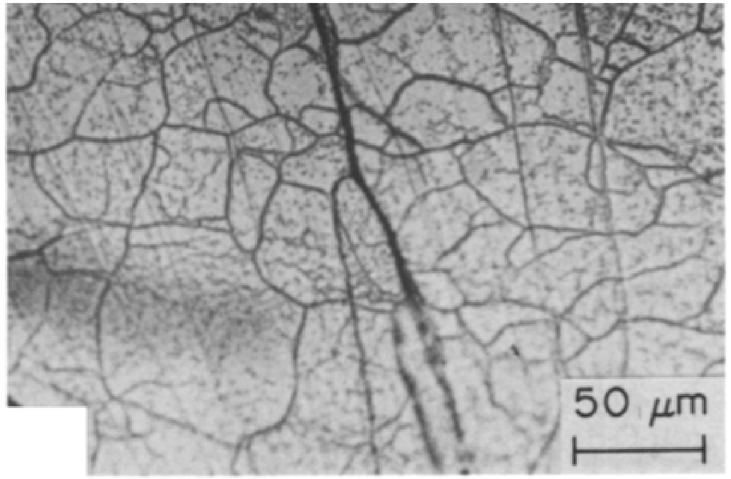
Mechanical Responses



Original ”Gedankenexperiment” from: Mughrabi, H. (1983) Dislocation wall and cell structures and long-range internal stresses in deformed metal crystals. Acta Metallurgica. Vol. 31. No. 9. pg. 1367-1379

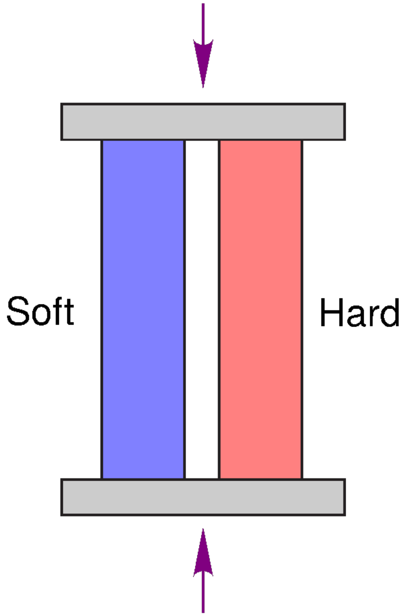
A “Gedankenexperiment”

Subgrains

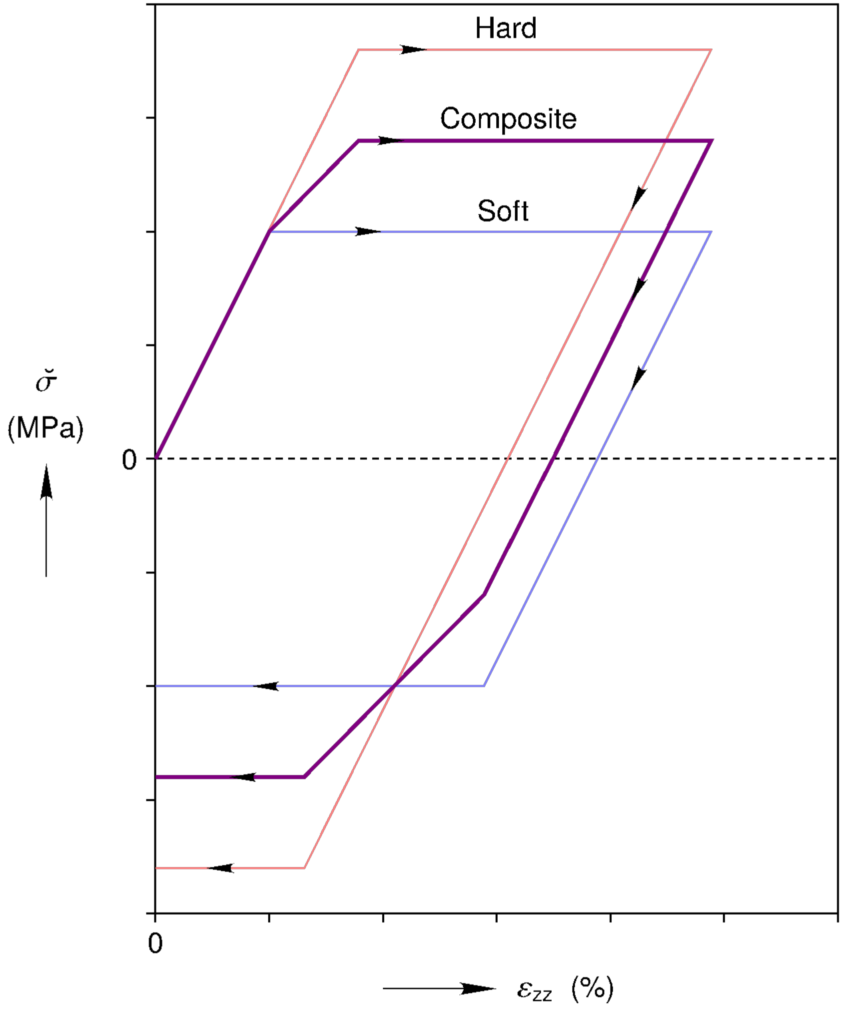


Schematic

$f = \breve{\sigma} A$

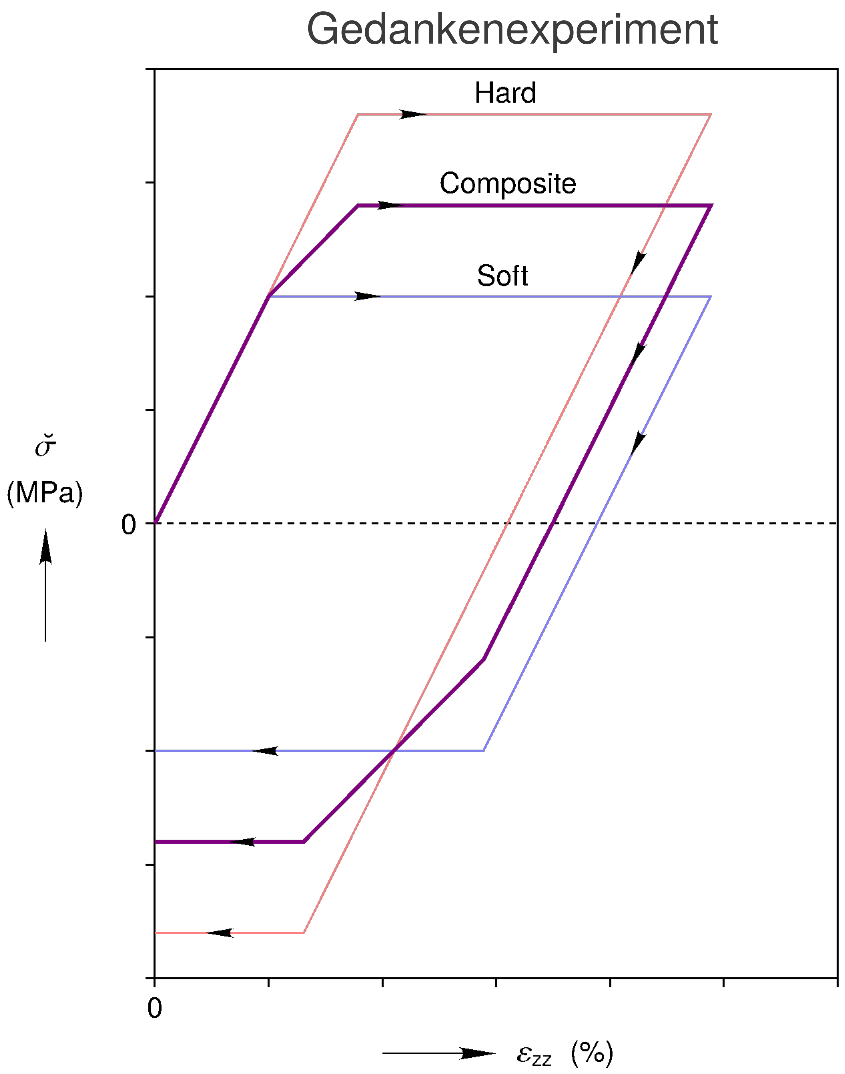


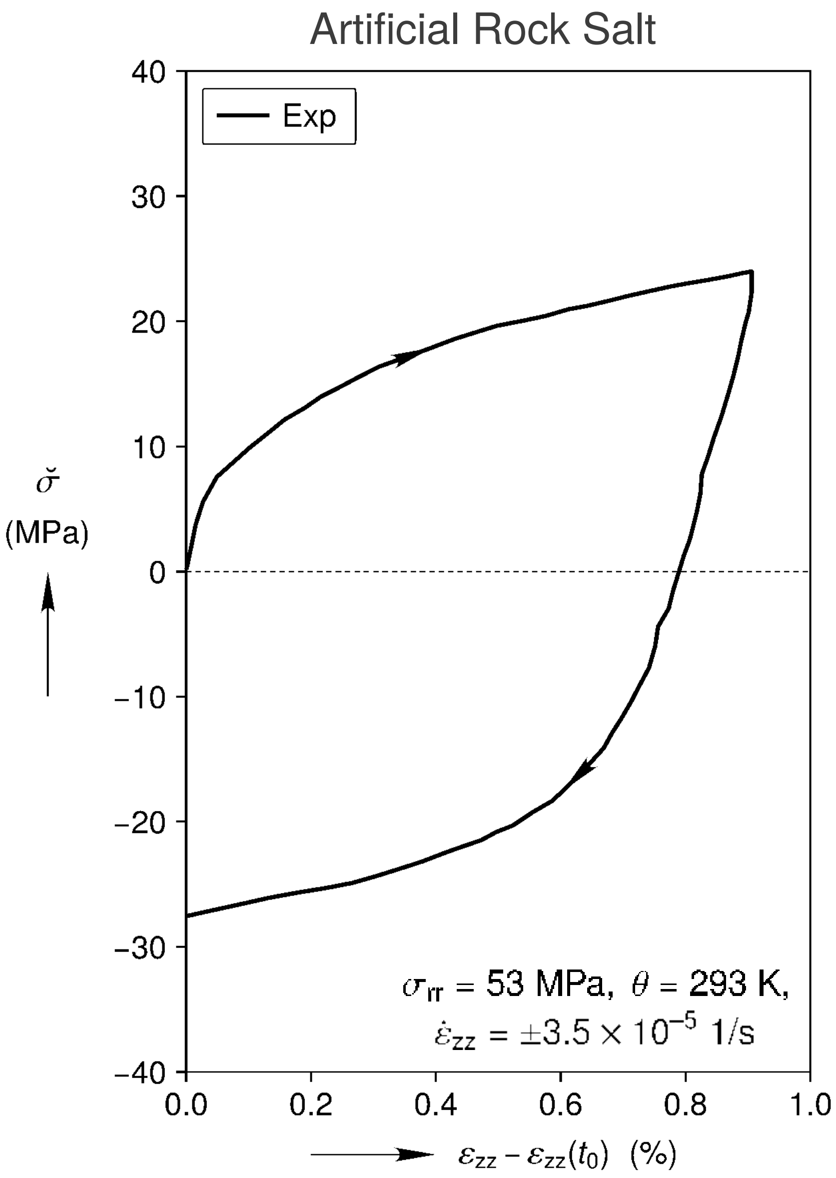
Mechanical Responses



Original ”Gedankenexperiment” from: Mughrabi, H. (1983) Dislocation wall and cell structures and long-range internal stresses in deformed metal crystals. Acta Metallurgica. Vol. 31. No. 9. pg. 1367-1379

Bauschinger Effect

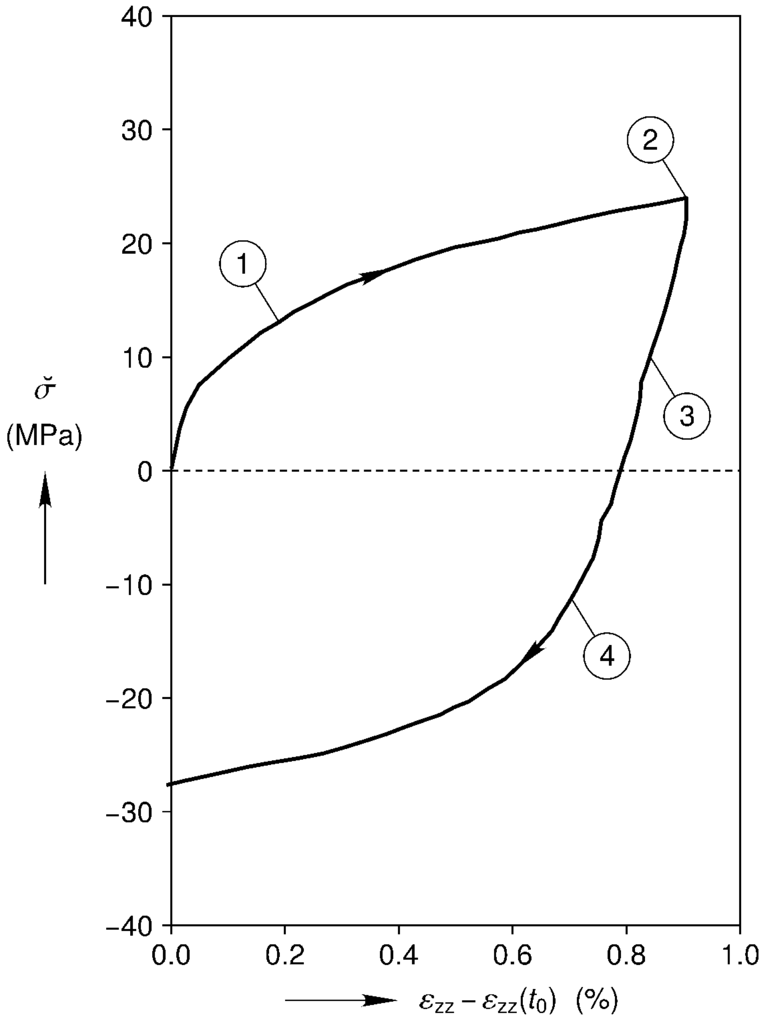


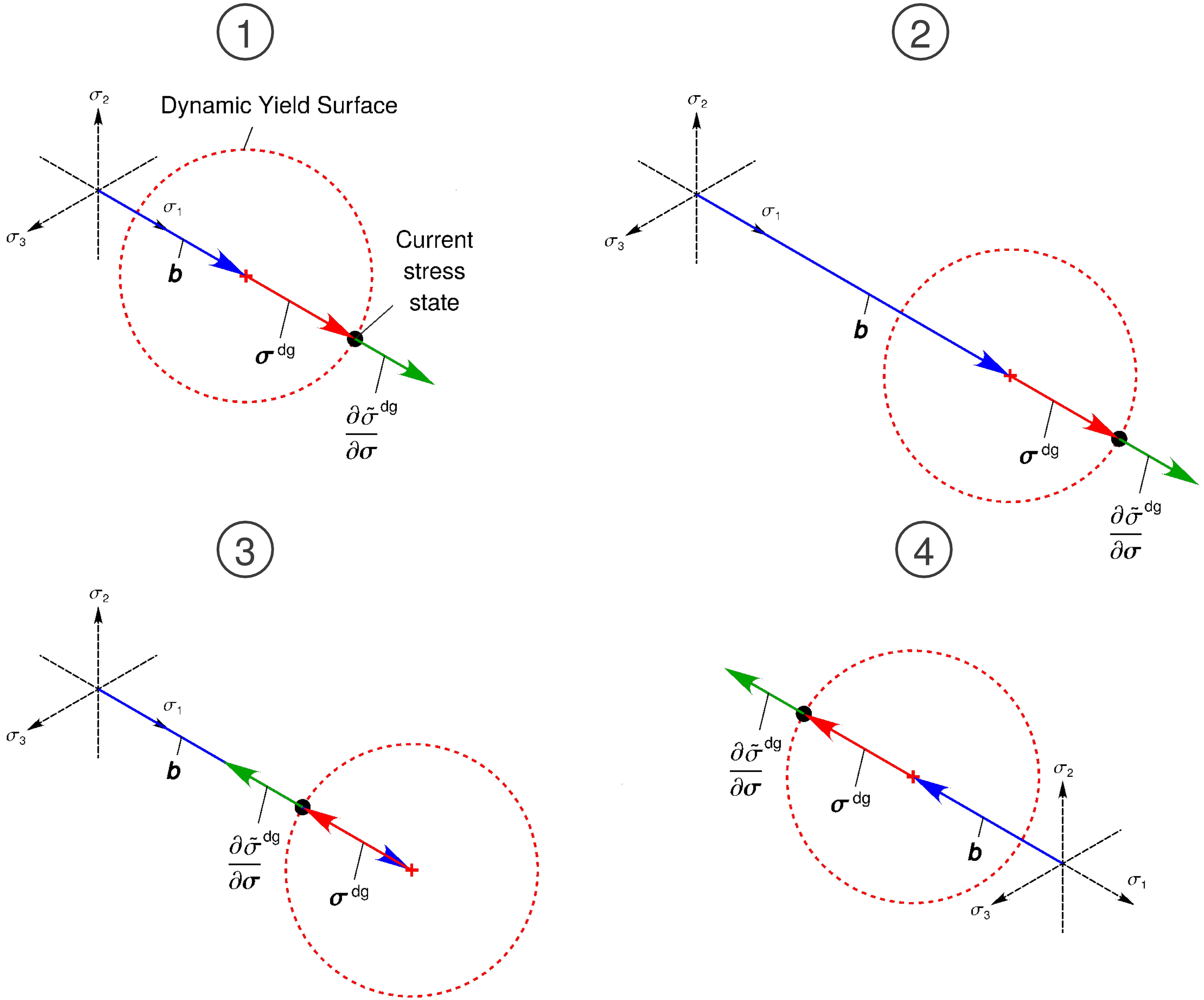


Experimental measurements from: Aubertin, M., Julien, M. R., Servant, S., and Gill, D.E. (1999) A rate-dependent model for the ductile behavior of salt rocks. Canadian Geotechnical Journal. Vol. 36. No. 4. pg. 660-674

Back Stress Hardening

Mechanical Response
Artificial Rock Salt

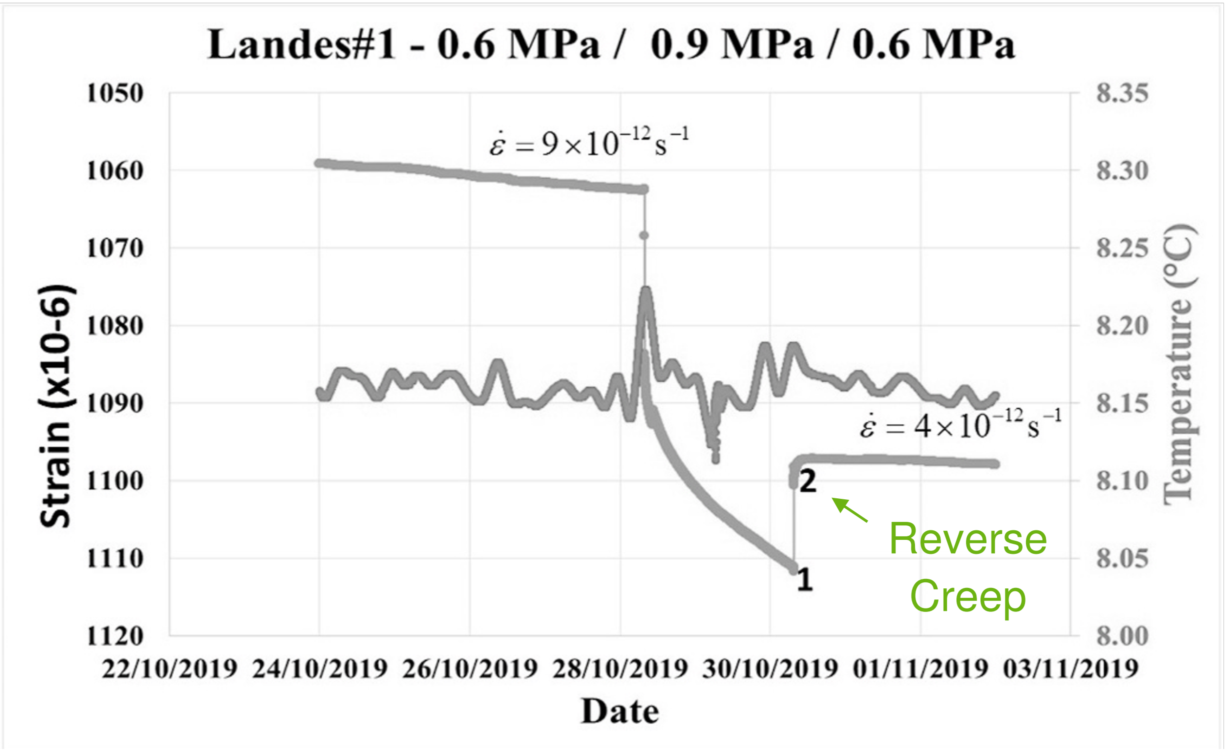




Experimental measurements from: Aubertin, M., Julien, M. R., Servant, S., and Gill, D.E. (1999) A rate-dependent model for the ductile behavior of salt rocks. Canadian Geotechnical Journal. Vol. 36. No. 4. pg. 660-674

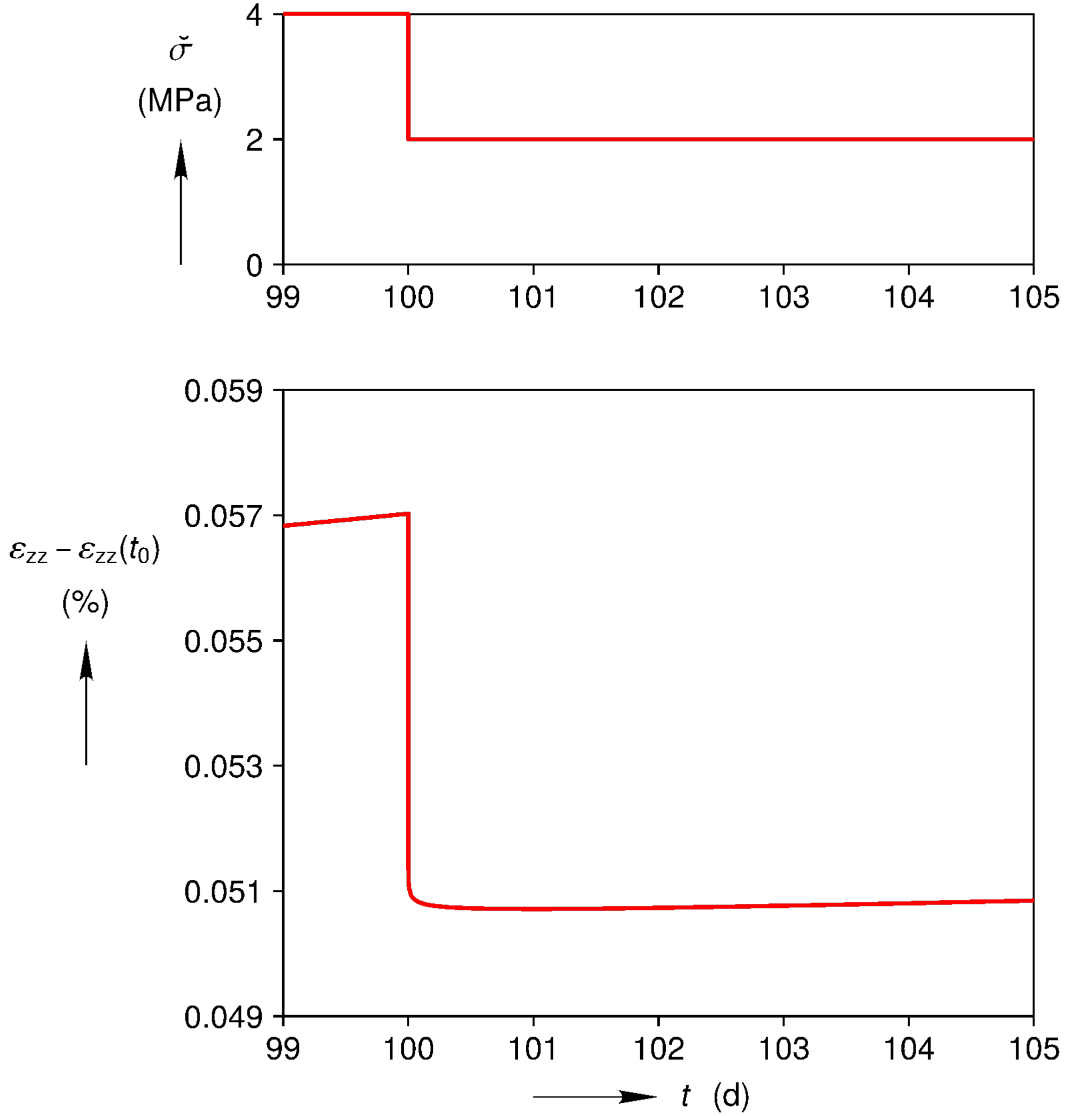
Reverse Creep at Low Stress and Room Temperature

Multi-stage Constant Stress Test on Landes Salt

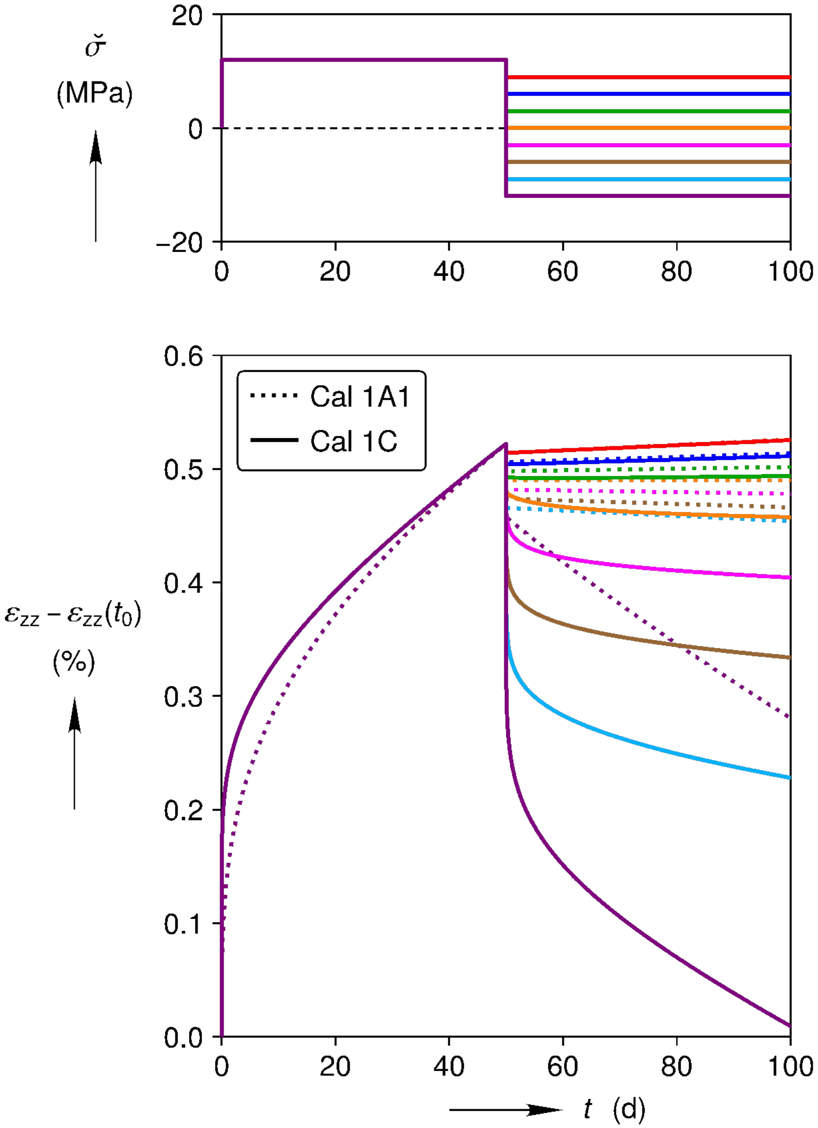


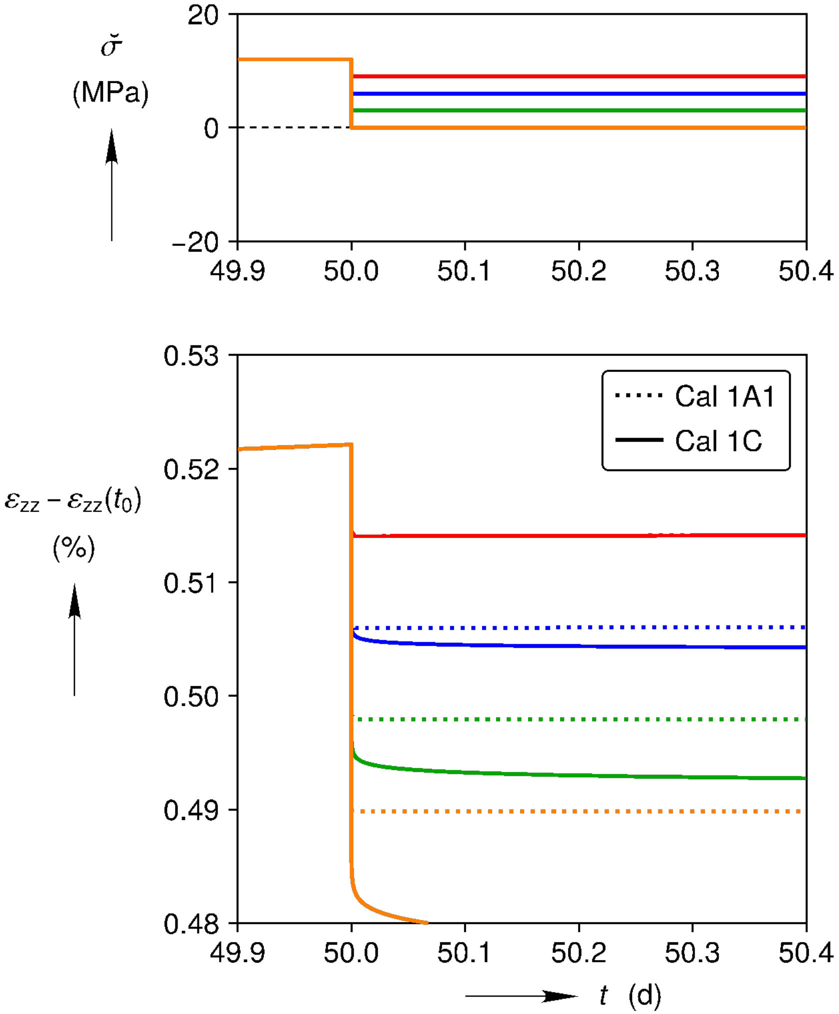
Ghardi, H., Bérest, P., Blanco-Martín, L., and Brouard, B. (Oct. 2020). "Determining upper and lower bounds for steady state strain rate during a creep test on a salt sample". In: International Journal of Rock Mechanics and Mining Sciences 134, p. 104452

Multi-stage Constant Stress Predictions (Cal 1C)
(different stresses than on Landes salt)



Room Temperature Stress Drop Behavior





Cal 1A1 strain shifted down by 0.067 % strain.

Gas Storage Cavern, Volume Loss with Wellhead Pressure Cycling