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Single-stage and Multi-stage Triaxial Deformation Experiments of Granite: Insights into Brittle Failure with Confinement Evolution

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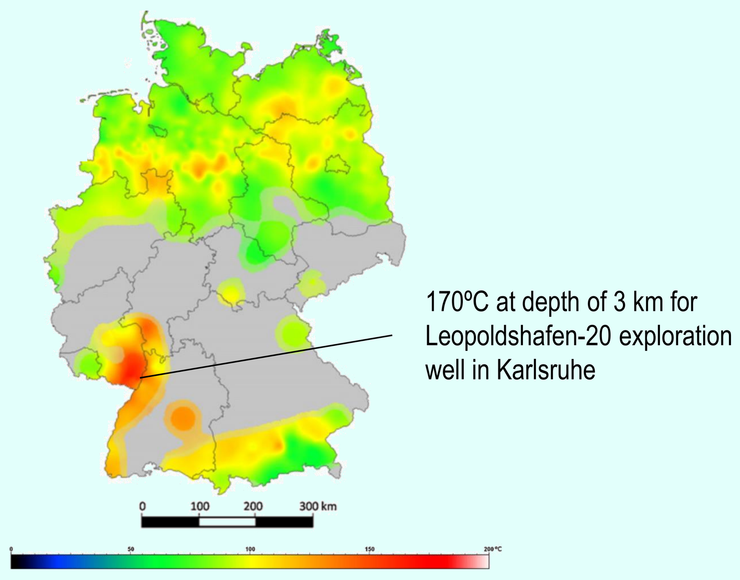
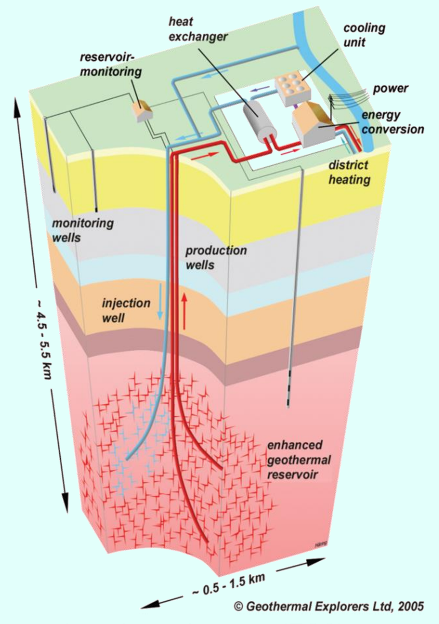
Introduction

Geothermal energy is heat from the Earth's interior, accessible through subsurface reservoirs of hot water or steam, and can be utilized for electricity generation and heating. It plays a crucial role in the energy transition by offering a stable, low-carbon energy source that is well-suited for base or steerable load supply, especially in densely populated areas. Despite its potential, advanced geothermal technologies for deep, high-temperature production and storage remain underdeveloped but could be enhanced through research, making geothermal a key solution for a secure, efficient, and flexible energy future in Germany.



Subsurface temperature in Germany at 2500 m below sea level (Agemar et al., 2012).



Enhanced geothermal system (EGS) (Geothermal Explorers Ltd, 2005).

To support the development of deep geothermal reservoirs, it is essential to understand the mechanical behavior of crustal rocks under realistic in-situ stress conditions. In this study, we investigate the deformation and failure behavior of granite - a key lithology in many geothermal contexts - using advanced triaxial testing techniques tailored for high-resolution control and measurement. **Single-stage and multi-stage confinement tests are carried out. For multi-stage tests, we evaluate damage evolution and failure behavior against consistent pre-peak strength criterion at each confinement stage, aiming to improve the interpretability and reliability of test results.**

Experimental Materials, Setup and Procedures

MTS HTHP triaxial rock test system

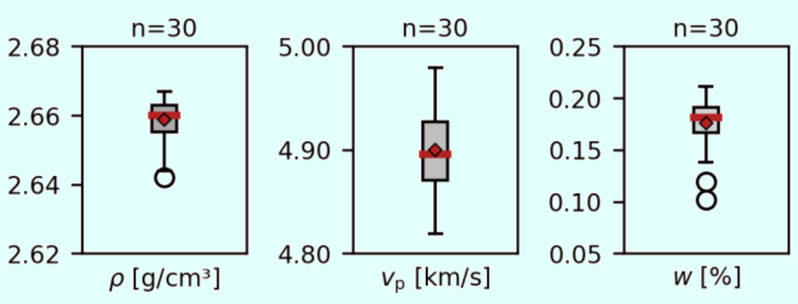
- Max. load: 2600 kN
- Max. confining pressure: 140 MPa
- Sample size: Ø54/70/100 mm, length 2-2.5xdiameter
- Hardware: MTS 816 Frame, Felx Test Controller
- Software: MTS TESTSUIT

✔ Smart control modes: displacement/stress/circumferential strain control
✔ Rock type-specific tuning for high-precision control
✔ Testing under in-situ stress conditions

Granite samples

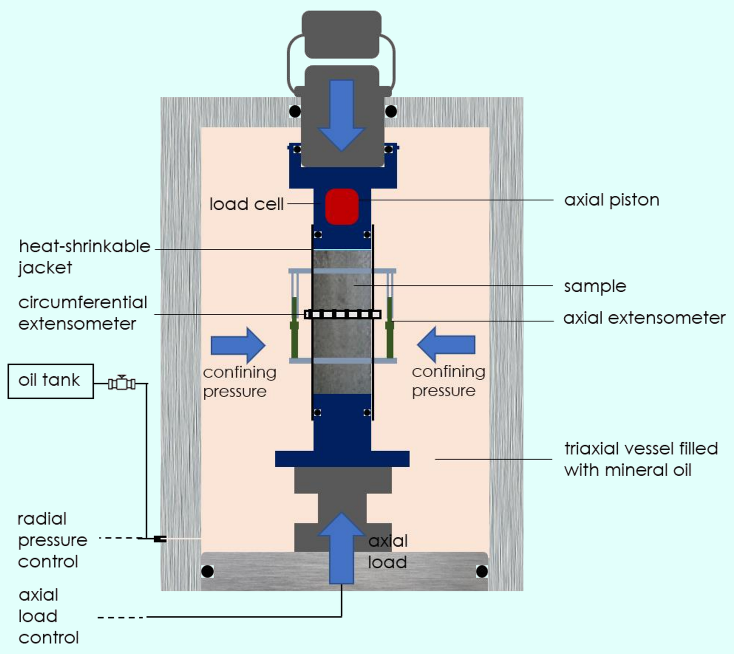
Portuguese granite.

- Homogeneous, fine crystalline
- Bulk density: 2.7 g/cm³
- Sample size: Ø54 x 125 mm cylinder.



Box plots of the homogeneity verifying tests (Schneider and Stutz, 2025).

Sample assembly inside pressure vessel

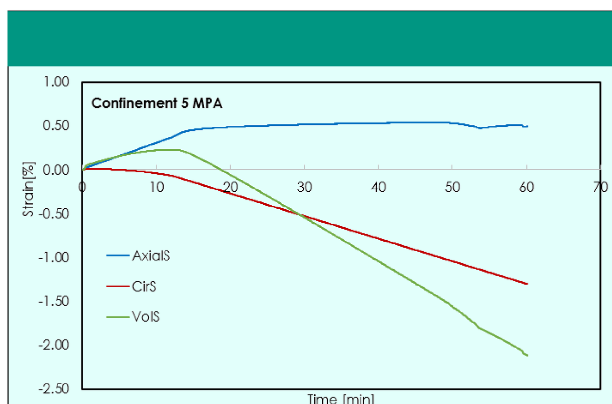


Single-stage confinement test (SST):
Higher accuracy and simpler interpretation were achieved by conducting tests at confinement levels of 5, 20, 40, 60, and 100 MPa, with three tests performed at each confinement level.

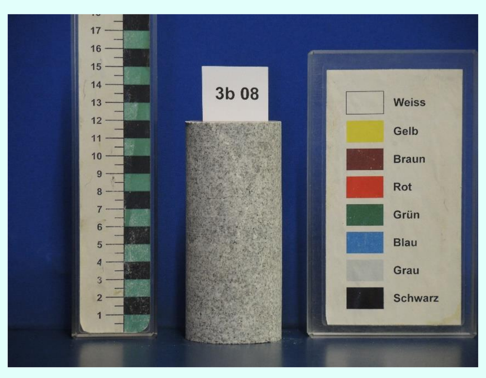
apply designed confinement → deform by axial strain control (0.03 %/min) to dilatancy point → deform by circumferential strain control (0.018 %/min) to failure

Multi-stage confinement test (MST):
The approach is more material- and time-efficient but introduces complexity in interpreting mechanical response due to potential cumulative damage and changing confinement history; it employs step-wise increasing (5–20–40–60 MPa) and decreasing (60–40–20–5 MPa) confinements, with axial strain control (0.03%/min) and circumferential strain control (0.018%/min) after the dilatancy point in each stage, and pre-peak detection applied in the first three stages.

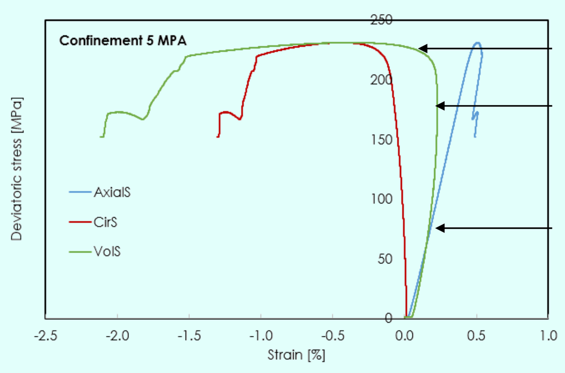
Results of Single-stage Tests



- Precise control by axial strain control and circumferential strain control after dilatancy point.

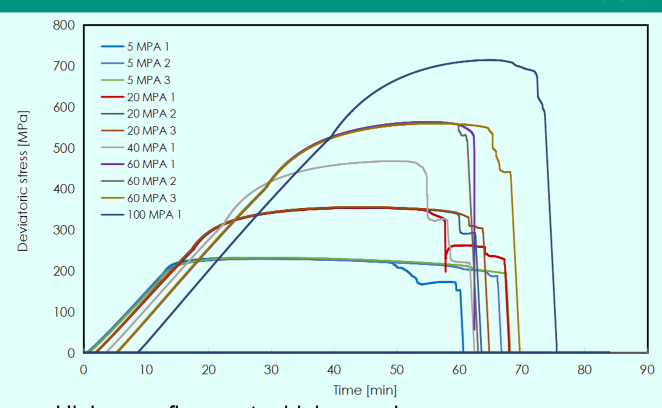
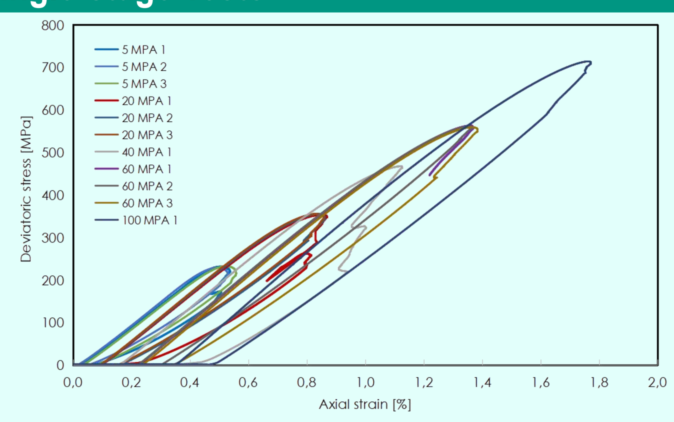


- Shear and axial splitting cracks are visible on post-test sample.

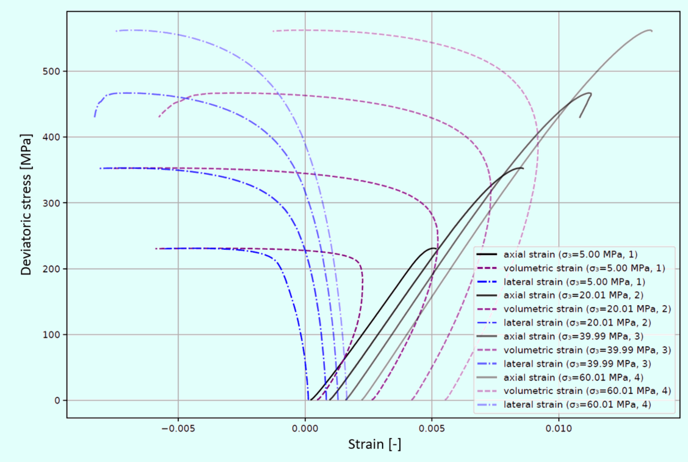
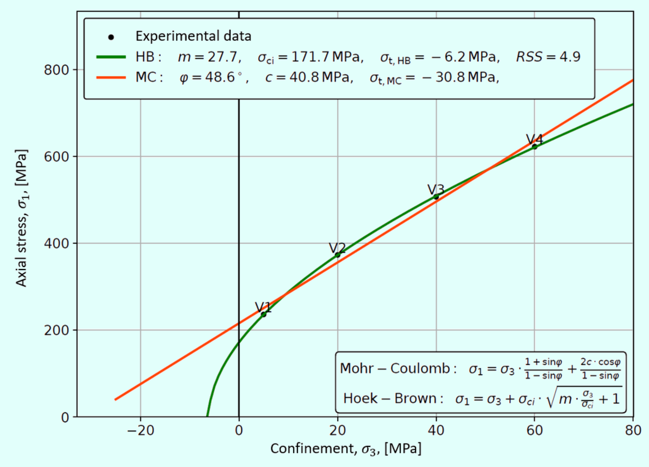


- Peak stress is well-defined but followed by axial strain softening.
- Ductile deformation dominates in post-peak regime.
- Net volumetric expansion is observed.

Results of Single-stage Tests

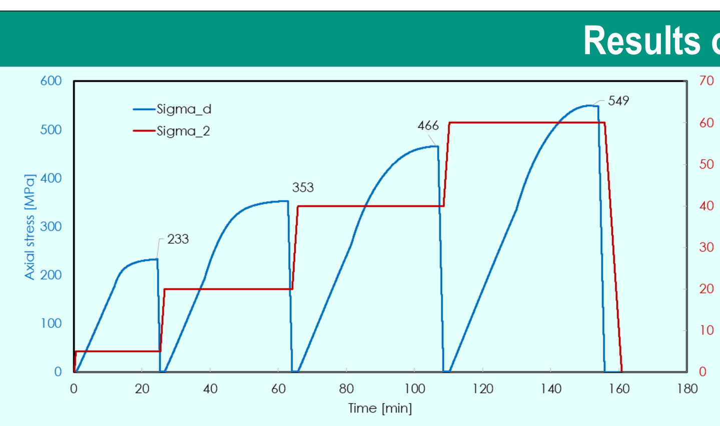
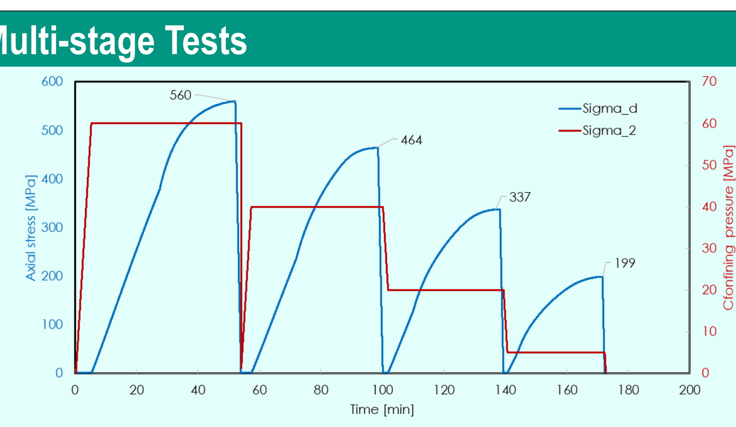



- Higher confinement – higher peak.
- Circumferential strain control allows stable and controllable propagation of the cracks in yielding region.
- With confinement, residual behavior is observed.

- Both Hoek-Brown and Mohr-Coulomb envelops provides granite properties in expected ranges, referred to Hoek and Brown, 1997.
- SST is accurate to provide in-situ parameters of granite for modelling, but cost- and time-demanding.

Results of Multi-stage Tests

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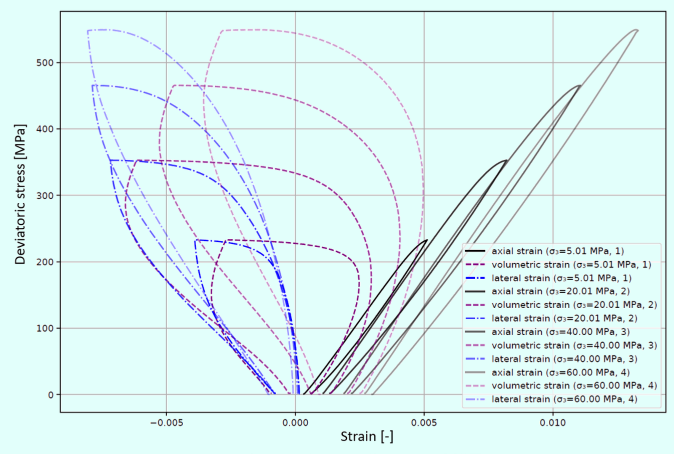
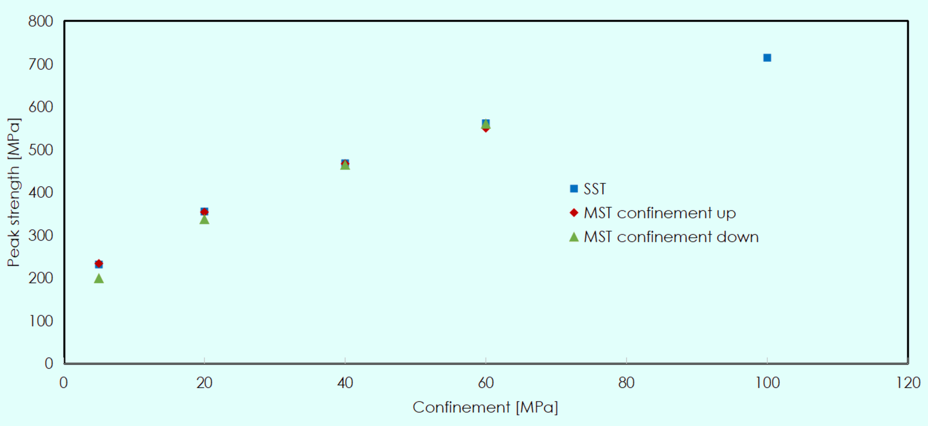
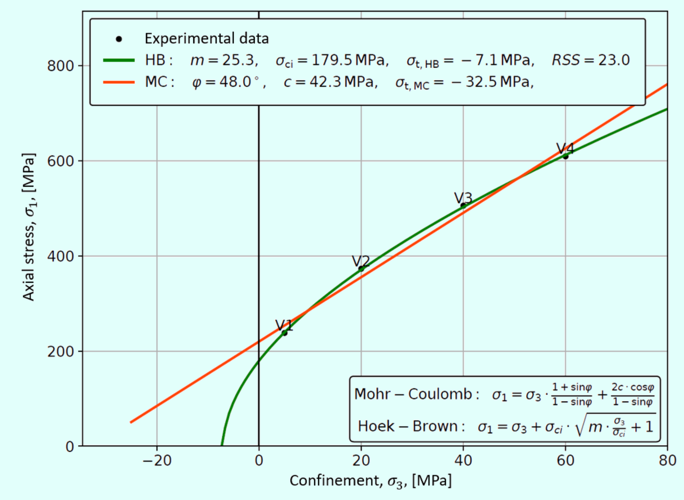


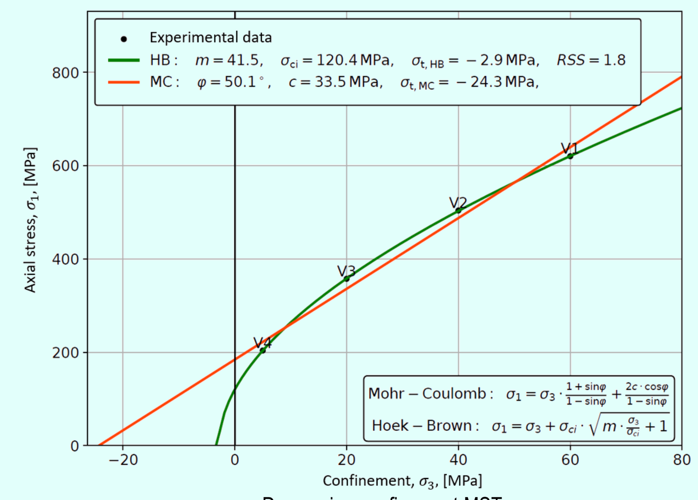
Increasing-confinement MST



- MST with increasing confinement through stages correlates with SST: repeat tests needed.



Increasing-confinement MST



Decreasing-confinement MST

- In increasing-confinement experiment, HB constant, m, for granite is 25.3. In decreasing-confinement one, m is 41.5.
- 0< confinement < 0.5 UCS is recommended by Hoek and Brown, 1997. Stage at confinement = 100 MPa will be added.

Conclusions and Outlook

Conclusions:

✓ Peak strength of granite increases systematically with confining pressure, consistent with established brittle–ductile transition behavior under triaxial loading.
✓ Multi-stage tests with increasing confinement yield peak strengths comparable to single-stage tests, indicating limited influence of cumulative pre-peak damage on peak strength at higher confinements.
✓ Circumferential strain accumulation across stages demonstrates irreversible deformation and progressive microcrack damage, even when peak strength is preserved.
✓ Decreasing-confinement paths result in lower and more scattered peak stresses compared to single-stage tests, highlighting the strong influence of stress path and confinement history on crack evolution.
✓ Circumferential strain control after the dilatancy point enables stable post-peak deformation and controlled crack propagation, allowing characterization of residual strength behavior.
✓ Hoek–Brown parameters derived from multi-stage tests are stress-path dependent, with higher m values observed during decreasing-confinement experiments, emphasizing the need to consider loading history in constitutive modeling.

Outlook:

❑ Extend multi-stage triaxial tests to higher intermediate principal stresses (e.g., confinement up to ~0.5 UCS, 100 MPa) to refine parameters under realistic in-situ stress conditions.

Acknowledgements

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