Geomechanical characterization of two granites to establish an experimentally based benchmark for numerical simulation – a laboratory study

Lucas Conrad Witte
Engineering Geology and Rock Mass Mechanics, Ruhr-University Bochum, Germany

Mandy Duda
Engineering Geology and Rock Mass Mechanics, Ruhr-University Bochum, Germany

Murat Aydin
Engineering Geology and Rock Mass Mechanics, Ruhr-University Bochum, Germany

Hossein Asghari Chehreh
Engineering Geology and Rock Mass Mechanics, Ruhr-University Bochum, Germany

Tobias Backers
Engineering Geology and Rock Mass Mechanics, Ruhr-University Bochum, Germany

ABSTRACT: Since decades, numerical models have been used to predict the behavior of the subsurface in civil and geological engineering projects. The validity of these codes must be tested against field observations or, more often, apparently simple laboratory experiments, whose outcome is typically known to the modeler. Therefore, there is a distinct need for an objective procedure to verify if codes are capable to mirror and predict supposedly simple, physical processes.

In this Study we have determined microstructural properties, geometric and grain densities, ultrasonic wave velocities, static moduli, uniaxial compressive strengths, tensile strengths, the time dependence of geomechanical properties, thermal and hydraulic properties.

Keywords: Rock mechanics, rock mass properties, laboratory experiments, granite.

1 INTRODUCTION

Accurate observation is the basis of natural science, leading to sound understanding of processes. This also applies to rock mechanics. Numerical simulation of rock mechanics systems should therefore ultimately comply with this basis of natural science, in particular if numerical simulations are applied in sensitive contexts such as radioactive waste disposal. Therefore, any numerical model shall be validated against observational data representing relevant processes to prove the robustness of the numerical implementation and create trust in the results of forward simulations. The international project DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments) was initiated some thirty years ago and had exactly this basis of natural science in mind. Today, simulation tasks have become even more complex and it is essential to validate their underlying assumptions and outcomes against data. In DECOVALEX this is realized with large scale experimental data. However, simulation software uses different mathematical frameworks that are not necessarily based on physics. Here, the initiative as described in this paper jumps in.

We are in the process of generating a comprehensive, high-accuracy benchmark set of mechanical and hydraulic laboratory experiment on granitic rock. As rock behavior is very sensitive to specimen preparation and loading configurations (Koelen et al. 2021) the data set is carefully documented in terms of sample collection, specimen preparation, experimental procedure, results, and data processing. The dataset aims at providing a validation to numerical codes for backward tuning and forward simulation. In the final stage the dataset will, hence, include open-label experimental results for model tuning and single-blinded results for validation of forward simulations. This will generate trust in simulations on predicting rock mass behavior in sensitive applications.

The laboratory program is carried out on Padang (China) and Epprechtstein (Germany) granite. In this paper we summarize the essence of results on microstructural and rock physical properties, thermal and hydraulic properties, uniaxial compressive and tensile strength, and static elastic moduli. We particularly focus on the time-dependence of mechanical properties, since temporal upscaling represents a major challenge in numerical modelling. The effect of loading rates and loading surface friction on strength data is also reported.

2 MATERIALS AND METHODS

2.1 Sample material

Padang granite G34 (China) and Epprechtstein granite (Germany) serve as sample material. The granites are of medium grain size (0,5 - 2 mm) and appear macroscopically isotropic. Padang granite is composed of 38 % quartz, 23 % alkali feldspar, 36 % plagioclase and 3 % biotite. The composition of Epprechtstein granite is 30 % quartz, 25 % alkali feldspar, 40 % plagioclase and 5 % biotite.

2.2 Specimen preparation

For basic rock physical characterization, determination of thermal properties and uniaxial compressive strength tests, cores of diameter D = 40 mm and length L = 80 mm and end surface parallelism of 0.02 mm are prepared. The diameter does not comply with the recommendation to exceed the largest grain size by a factor of 10. We validate this assumption on purpose, because sample material from exploration campaigns, e.g. boreholes, is generally limited in quantity. For splitting tensile strength tests, specimens of diameter D = 40 mm and length L = 20 mm are prepared. Drilling, sawing and grinding are done using diamond drill bits and grounding plates with water as cooling fluid. Before each test, the specimens are oven-dried at 60 °C for at least 24 hours. All specimens within a sample are drilled in the same direction.

2.3 Methods

2.3.1 General rock physical properties

Bulk densities are determined through the ratio of mass to bulk volume of oven-dried specimens. Ultrasound P- and S-wave velocities are determined in axial specimen direction using a standard measurement device (Geotron Elektronik) with S-wave sensors. Two identical ultrasound sensors, one serving as source and one as receiver, are pneumatically loaded to the end faces of the specimens with approximately 800 mbar. Rubber sheets (1 mm thickness) are used as coupling medium. The waveform generator generates a rectangular source with a frequency of about 350 kHz. Signals are semi-automatically analyzed using the software LightHouse UMPC that considers system travel time (Rentsch & Krompholz 1961).

2.3.2 Thermal properties

Thermal properties are determined using C-Therm's Trident system with the Modified Transient Plane Source (MTPS) on cylindrical specimens (Harris et al. 2014). The semi-automatic measurement technique applies a current to the sensor's spiral heating element that provides a small amount of heat, typically of 1 to 3 K, which is one-dimensionally transferred into the measured end face of the sample (ASTM 2021). The thermal feedback between specimens and sensor results in an increase in the sensor voltage used to determine the thermal properties in the direction perpendicular to the sensor's surface, i.e., thermal conductivity, thermal effusivity, and (derived) heat capacity. Specimens and sensors are coupled using distilled water. Coupling is improved by a 500 g weight that is put on top of the sensors during measurement.

2.3.3 Mechanical properties

To determine the uniaxial compressive strength (UCS) specimens are placed in a stiff 4 MN loading frame centered between the loading plates, which feature a spherical seat. In certain experiments a 0.5 mm thick Teflon sheet is placed between loading platen and specimen to reduce friction. A radial strain chain is placed at the centre of the specimen. The uniaxial compressive strength test is conducted servo-controlled with grade 1 testing equipment. During testing, axial load is applied until failure occurred. The axial piston advances with a constant velocity resulting in a nominal strain-rate of about 10^{-5} mm/mm/s. Axial stresses and strains are calculated based on the cross-sectional area of the sample (disregarding effective contact between piston and sample) and maximum specimen length, respectively. UCS σ_c is derived from the maximum in the stress-strain-relation. The deformation modulus V and the Poisson's ratio υ are determined at an axial stress in the range from 40 % to 60 % of σ_c (Mutschler 2004) using axial strains that are calibrated for system characteristics.

For splitting tensile strength tests (BDT) a rock disc is placed in a steel loading jaw. After centering the sample an initial load of 200 N is applied. Further strain is applied with a rate of 1,5 µm/s until failure occurred. Tensile stress is determined from load F, diameter D and sample length L after Ulusay & Hudson (2007) and DGGT (2008). Splitting tensile strength $\sigma_{t,sp}$ is determined from the maximum in stress-strain-relations provided by splitting tensile strength tests.

2.3.4 Hydraulic properties

Permeability is determined on a cylindrical rock specimen placed in a Hoek cell. The rubber sleeve of the Hoek cell is pressed against the lateral surface of the specimen by applying a confining pressure, so that circulation of the axially introduced fluid along the outer specimen surface is prevented. At the specimen's end faces, the fluid up- and downstream (distilled water) is connected to the pore pressure system by loading plates with concentric reliefs. Using Vindum Pump Engineering pumps, the specimen is first saturated to a set pore pressure until fluid uptake stopped. Three different pore pressure gradients of 0.2, 0.4, and 0.6 MPa between upstream and downstream are applied at a confining pressure of 5 MPa and a constant downstream pressure of 2 MPa Permeability was derived following Darcy's law with average volumetric flow rates (Hölting & Coldewey 2019).

2.3.5 Laboratory program

Table 1 provides an overview of the experimental laboratory program with 30 tensile strength tests and 58 uniaxial compressive strength tests.

Table 1. Summary of the laboratory program (UCS and BDT). 54 Padang granite specimens and 34 Epprechtstein granite specimens were investigated. ./. denotes that no experiments of that kind were performed to this point.

	unit	strain rate	Padang Granite		Epprechtstein Granite	
			no Teflon	Teflon	no Teflon	Teflon
σ_t	[MPa]	$1.5 \cdot 10^{-4}$	7	./.	3	./.
		$1.5 \cdot 10^{-3}$	7	./.	3	./.
		$1.5 \cdot 10^{-2}$	7	./.	3	./.
σ_c	[MPa]	10^{-7}	./.	3	./.	1
		10^{-6}	6	2	6	1
		10^{-5}	6	3	8	1
		10^{-4}	6	4	6	1
		10^{-3}	1	2	./.	1

3 RESULTS & INTERPRETATION

3.1 *General rock physical and hydraulic characterization*

Table 2 presents the rock physical and hydraulic characterization results. Densities of Padang and Epprechtstein granite are similar. The average geometric densities are 2,635 kg/m³ and 2632 kg/m³, and the grain densities 2,651 kg/m³ and 2649 kg/m³, respectively. In both granites, the connected as well as the total porosity is less than 1 % along with a low permeability of $< 10^{-19}$ m². For ultrasonic wave velocities and thermal properties, higher values can be observed for the Epprechtstein granite. Ultrasonic P- and S- wave velocities of Epprechtstein granite are about 400 m/s and 260 m/s faster. Thermal properties differ marginally; slightly higher values are observed for Epprechtstein granite.

Table 2. General rock physical properties of Padang and Epprechtstein granite (average and standard deviation out of 57 specimens).

	Unit	Padang granite	Epprechtstein granite
geometric density	[kg/m³]	2,635 ± 3	2,632 ± 3
bulk density	[kg/m³]	2,651 ± 7	2,649 ± 1
connected porosity	[%]	0.63 ± 0.33	0.48 ± 0.18
total porosity	[%]	0.66 ± 0.18	0.97 ± 0.12
permeability (water)	[m²]	$< 10^{-19}$	$< 10^{-19}$
P-wave velocity	[m/s]	4,264 ± 147	4,669 ± 20
S-wave velocity	[m/s]	2,383 ± 59	2,644 ± 33
thermal conductivity	[W/mK]	3.26 ± 0.27	3.48 ± 0.34
thermal effusivity	[$Ws^{1/2}/m^2K$]	2,566 ± 130	2,677 ± 157
heat capacity (derived)	[J/kgK]	770 ± 15	786 ± 18

3.2 *Mechanical characterization*

Table 3. Mechanical properties of Padang and Epprechtstein granite at different strain rates (average and standard deviation). A Teflon sheet of thickens 0.5 mm was put between specimen and loading device in certain experiments to reduce loading induced surface friction. ./. denotes that no experiments of that kind were performed to this point.

	unit	strain rate	Padang granite		Epprechtstein granite	
			no Teflon	Teflon	no Teflon	Teflon
σ_t	[MPa]	$1.5 \cdot 10^{-4}$	8.6 ± 1.1	./.	9.1 ± 0.7	./.
		$1.5 \cdot 10^{-3}$	8.4 ± 1.5	./.	9.9 ± 0.0	./.
		$1.5 \cdot 10^{-2}$	10.8 ± 1.3	./.	10.2 ± 0.3	./.
σ_c	[MPa]	10^{-7}	./.	137 ± 3	./.	86
		10^{-6}	195 ± 15	145 ± 0	139 ± 3	109
		10^{-5}	216 ± 7	153 ± 9	151 ± 8	111
		10^{-4}	216 ± 28	177 ± 14	150 ± 5	116
		10^{-3}	258	187 ± 13	./.	135
Young‘s modulus	[GPa]	10^{-7}	./.	56 ± 1	./.	34
		10^{-6}	55 ± 1	57 ± 0	49 ± 5	38
		10^{-5}	56 ± 3	57 ± 3	48 ± 6	44
		10^{-4}	55 ± 3	61 ± 5	49 ± 5	37
		10^{-3}	./.	63 ± 4	./.	42

The results of the mechanical characterization are shown in Table 3. The tensile strength of Padang and Epprechtstein granite are similar and show no strain rate sensitivity beyond sample-to-sample variability. The UCS results suggest a sensitivity to strain rate for both rocks covering five orders of magnitude (c.f. Figure 1), whereas Young's modulus does not conclusively (Table 3). Reproducibility of UCS is low at mid-range loading rates for the set-up without the friction reducing Teflon sheet introduced; the Teflon sheet results in lower measured strength and less scatter. Introduction of a Teflon sheet also reduces the Young`s modulus and its scatter.

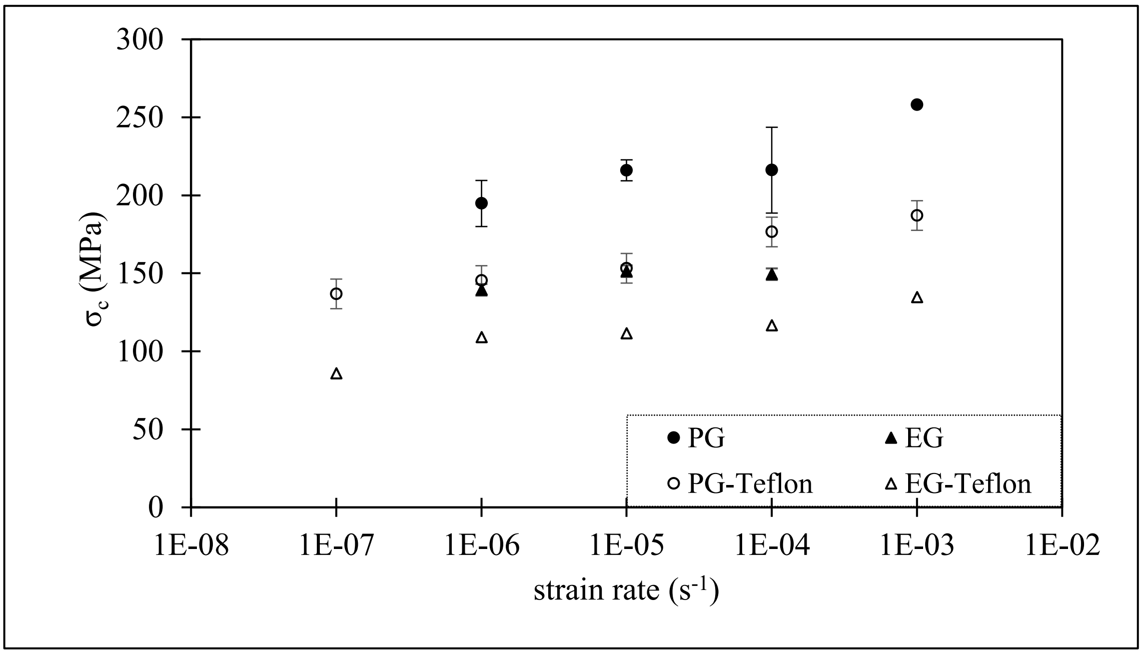

Figure 1. Uniaxial compressive strength of Padang and Epprechtstein granite as a function of strain rate. A Teflon sheet between loading plate and specimen appears to lower the measured strength.

4 DISCUSSION AND CONCLUSION

This paper summarizes first results of an initiative to produce a comprehensive data set for tuning and validation of numerical simulations for rock mechanics applications. The ongoing work will yield in basic data for model tuning and single-blinded experimental results for validation of the predictive capabilities of numerical codes.

The data set presented here comprises data for Padang and Epprechtstein granite. The experimental procedures follow international standards and are documented in all details for further reference.

The results of UCS experiments indicate a strain rate sensitivity, which is considered to be attributed to subcritical crack growth, its time-dependent kinetics and resulting nonlinear viscoelastic behavior (Grady & Kipp 1987, Grady & Lipkin 1980, Chong et al. 1980, Paterson & Wong 2005 and Duda & Renner 2013). Applying a Teflon sheet between loading platen and specimen resulted in a reduction of the measured strength, which might indicate preparational uncertainties of end faces that cause stress concentrations (Koelen et al. 2021). Although great care was taken that end faces were plane parallel and even, resulting in an extraordinarily long preparation time per sample, the high stiffness and strength of granitic rocks are particularly sensitive to even small deviations in sample geometry. Teflon might therefore also have lead to a smoother stress distribution causing the reduction in measured strength. The reproducibility of uniaxial compressive strengths increased significantly, but to the cost of a hard-to-calibrate axial strain, that is significantly affected by the deformation of the Teflon plates. Consequently, stress-strain relations and Young's moduli, both required for numerical modelling, of experiments performed with Teflon plates are subject to larger uncertainties. An apparent time dependence of Young's moduli might be artificially introduced by the viscoplastic deformation of the Teflon plates. We do not expect this to affect the strength values, because porosity is very low in our granites prohibiting any penetration of Teflon into pores, but the interaction between Teflon and initiating axial splitting might affect the overall macroscopic failure pattern.

We plan on overcoming this problem by using a lubricant that does not alter measured axial strains but reduces friction so that uniaxial compressive strengths and their rate-dependence can be reflected. The use of lubricants is then also essential for triaxial deformation experiments to provide consistent boundary conditions for uniaxial and triaxial deformation, whose results are required to derive failure and friction criteria for numerical modeling.

ACKNOWLEDGEMENTS

This work is funded by the Swedish Radiation Safety Authority. We acknowledge Maria Norden, Biruk Woldemedhin and Calle Pettersson of SSM for discussions and improvements.
Initial discussions about the need for such data go back to late Ove Stephansson and in particular Flávio Lanaro (SSM at that time). Furthermore, we are grateful to Claudia Thoenes for assistance with the laboratory experiments.

REFERENCES

ASTM D7984-16. 2021. *Standard Test Method for Measurement of Thermal Effusivity of Fabrics Using a Modified Transient Plane Source (MTPS) Instrument.* American Society for Testing and Materials: West Conshohocken

Chong, K.P., Hoyt, P.M., Smith, J.W., Paulsen, B.Y. 1980. Effects of strain rate on oil shale fracturing. Int J Rock Mech Min 17:35–43

Deutsche Gesellschaft für Geotechnik e.V. 2008. *DGGT Empfehlung Nr. 10 Indirekter Zugversuch an Gesteinsproben – Spaltzugversuch*. Bautechnik 85, Heft 9, pp. 623-627

Duda, M. & Renner, J. 2013. The weakening effect of water on the brittle failure strength of sandstones. *Geophysical Journal International* 192, 1091–1108

Grady, D., & Kipp, M. 1987. Dynamic rock fragmentation. In: *Atkinson BK (ed) Fracture mechanics of rock*. Academic Press, London, pp 429–475

Grady, D. & Lipkin, J. 1980. Criteria for impulsive rock fracture. Geophys Res Lett 7:255–258 Dynamic rock fragmentation. In: *Atkinson BK (ed) Fracture mechanics of rock*. Academic Press, London, pp 429–475

Harris, A., Kazachenko S., Bateman, R., Nickerson, J. & Emanuel, M. 2014 *J. Therm. Anal. Calorim.* 116 1309 1314

Hölting, B. & Coldewey, W.G. 2019. *Hydrogeologie – Einführung in die Allgemeine und Angewandte Hydrogeologie*. 8. Auflage. Springer Verlag Berlin.

Koelen, K., Alber, M., Duda, M. & Backers, T. 2021. Effect of sloppy sample preparation on results from uniaxial compressive strength tests. *IOP Conf. Ser.: Earth Environ. Sci. 833 012030.* September 2021, Turin, Italy

Mutschler, T. 2004: *Neufassung der Empfehlung Nr. 1 des Arbeitskreises "Versuchstechnik Fels" der Deutschen Gesellschaft für Geotechnik e.V.: Einaxiale Druckversuche an zylindrischen Gesteinsprüfkörpern.* Ernst & Sohn Verlag, Bautechnik 81, 10, pp. 825-834

Rentsch, W. & Krompholz, G. 1961. *Fachzeitschrift der Bergakademie Freiberg* **7** 492-504

Paterson, M.S. & Wong, T.F. 2005. Experimental Rock Deformation – The Brittle Field. 2nd Edition. Springer Verlag. 348 p.

Ulusay, R. & Hudson JA. 2007. *The complete ISRM suggested methods for rock characterization, testing and monitoring. 1974-2006.* International Society for Rock Mechanics, Commission on Testing Methods, Ankar