FUTURE CIRCULAR COLLIDER STUDY / DOCTORAL THESIS REPORT

Description of laboratory analyses performed at Montanuniversität Leoben (MUL) in Leoben, Austria

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Content

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1. Introduction

An essential part of the subsurface infrastructure construction and re-use of excavated rock material as part of CERN's Future Circular Collider (FCC) study is a thorough understanding of its underlying geology. Hence, rock material has been tested at three distinct laboratory locations, respectively ETH Zurich, University of Geneva and Montanuniversität Leoben. Based on geomechanical, petrophysical, mineralogical and geochemical laboratory analyses, further implications are derived.

This document describes the laboratory measurements performed at Montanuniversität Leoben, Austria from November 2020 to March 2021, within the scope of FCC's PhD study on "Geomechanical, petrophysical and sediment-petrographical classification of molasse rock in the Geneva Basin".

The laboratory measurements at Montanuniversität Leoben include:

1. Compressional (P) and shear (S) wave velocity,
2. Cerchar abrasivity (CER),
3. Brazilian tensile strength (BRA),
4. Point load (PL).
5. Laboratoire Central des Ponts et Chaussees (LCPC) and
6. Uniaxial compressive strength (UCS) tests.

For a detailed scientific description, the reader is referred to literature and technical data sheets cited at the end of each section. The purpose of this laboratory report is dedicated to methodological descriptions only. Scientific interpretations and further conclusions are stated in the PhD thesis by Maximilian Haas.

2. Sample origin, sample number & analyses

Original samples were collected at Swiss (Lucerne) and French (Boussens) core facilities as well as from outcrops along the current FCC subsurface tunnel alignment according to CERN's CDR report (December 2018) featuring samples from the Quaternary and Molasse (OSM) formations.

Two sample types were analysed:

1. Drill cores (from Peissy-I well) and
2. Plug samples from
   a. outcrops and
   b. boreholes, namely Gex-CD-01 to -07 drilled from half-cores.

Plugs with dimensions of 2-2.5 cm in diameter and 2-8 cm in length were drilled from half cores and outcrop blocks and split in different fractions for subsequent laboratory analyses. Table 1 gives an overview of the number of samples per analysis.

Table 1: Overview of analyses performed at MUL with respective sample number and sampling location (well).

type of analysis	sample amount	sample location
P- and S-wave ultrasonic velocity	282	Point 1 (C-wells), Peissy-I, Sarzin, Mornex, GEX-CD-1 to GEX-CD-7
Cerchar	147	
Brazilian tensile strength	99	
Point load	116	
Laboratoire Central des Ponts et Chaussees (LCPC)	65	
Uniaxial compressive strength (UCS)	153	

All samples have been described sedimentologically and geologically prior to all subsequent analyses.

3. Sample shipment

Due to the COVID-19 pandemic, measurements could not be performed personally but were outsourced to the rock mechanics laboratory at Montanuniversität Leoben. Consequently, samples have been shipped to Leoben via truck transport for geomechanical and petrophysical analyses to compensate potential time delays. In total, about 512 kg of rock material were sent.

Figure 1: One out of two shipment boxes. Each sample was bubble wrapped to prevent any damage on rock samples.

4. Sample preparation

4.1. Drilling of plug samples

Plugs were drilled from well core samples and outcrop blocks using a driller machine and further prepared on abrasive tables to create planar surfaces for subsequent laboratory analyses.

Figure 2: Overview of machine equipment to drill and prepare the plug samples. Left: Driller to drill plugs from blocks and/or cores, middle: result of a drilled plug, right: grinding of plug sample with rough (right table) and fine (left table) abrasives under flowing water.

4.2. Preparation of drill cores

Each drill core was prepared properly following standard procedures and norms in terms of length to diameter ratios and planar surfaces for each analysis as described in the following sections.

5. Compressional and shear wave velocity via ultrasonic measurements

In an isotropic elastic material two wave types, respectively Vp and Vs are observed. They are linked to elastic parameters such as Young's modulus, which is defined as the ratio of axial stress to axial strain in a uniaxial stress state, bulk modulus, k, as the ratio of hydrostatic stress to volumetric strain and shear modulus, μ, as the ratio of shear stress to shear strain. Further derivations using Poisson's ratio, which depicts the negative ratio of lateral strain to axial strain in a uniaxial stress state can be drawn. Wave velocity is controlled by elastic properties of rock forming minerals, their fractional volume, their contact, cementation, porosity, saturation, pressure, temperature and pore fluid. In magmatic and metamorphic rocks, it is mainly influenced by the effects of cracks, fractures and pores, their anisotropy, temperature and pressure. For sedimentary rocks, porosity and matrix are the most important factors. In an anisotropic material a directional dependence can be indicated. With increasing pressure pore, fracture and crack closure occurs and velocities increase. With increasing temperature velocity decreases because of the change of the elastic properties of the rock forming minerals, the change of the pore filling and changes in contact conditions of the grains. Ultrasonic velocities are sensitive to fluids exhibiting strong influence on compressional wave velocity and a weak influence on shear wave velocity.

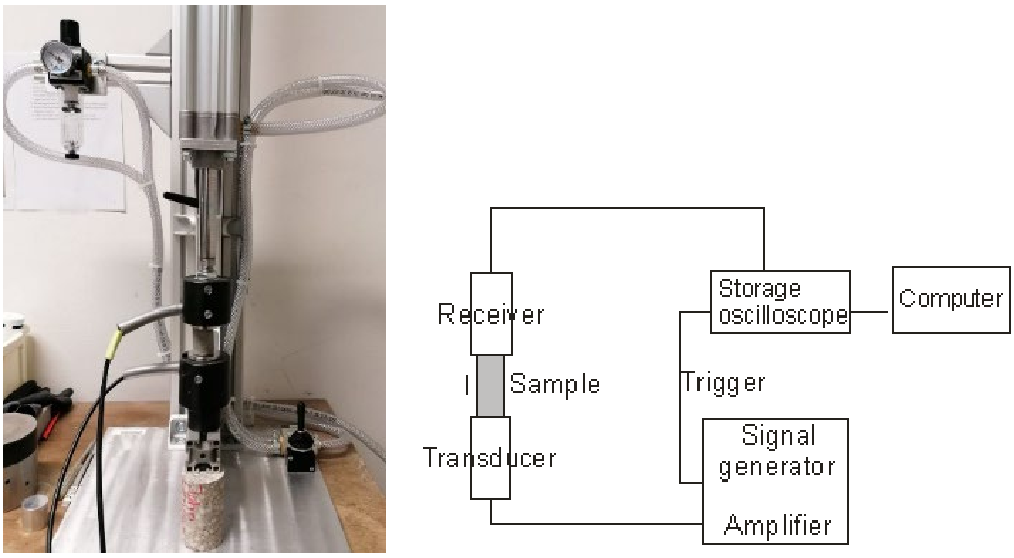


Figure 3: Ultrasonic device (left) and illustration of measurement procedure (right).

The compressional wave velocity was determined with an ultrasonic device. The sample was fixed between a transmitter and receiver with a contact agent on both sides (ultrasonic gel) and a pressure of 5 bar was applied continuously. Transducers comprised piezoceramic systems (Type: UPE, Geotron Elektrik, Germany) designed for compressional and shear wave measurements. A Dirac impulse was sent from a signal generator (Geotron Elektrik, Germany) to the transducer and resulted in a mechanical pulse passing through the sample. The arriving signal was visualized via a storage oscilloscope (Cleverscope, New Zealand). A program picked first arrivals and calculated velocities. At the start of each new measurement cycle, delay time between electrical impulse and mechanical pulse (dead time) was determined and corrected for all measurements. The onset of Vp and Vs were detected with the Akaike Information Criterion Picker (AIC). The AIC is an autoregressive method and assumes measurements, which are divided into local stationary segments, whereby the sections before and after an onset of a specific waveform state two different stationary processes. A phase onset is then identified by the position, where the AIC values show a minimum (least-square fit). A global minimum of AIC refers to the onset of a compressional wave arrival, a local minimum to an onset of a different phase is associated to the onset of the shear wave.

References & further reading:

- Gegenhuber, N. and Steiner-Luckabauer, C., 2012, vp/vs Automatic Picking of Ultrasonic Measurements and their Correlation of Petrographic Coded Carbonates from Austria, 74th EAGE Conference & Exhibition, Copenhagen. Anal. 14, 99–123.
- Mavko, G., Mukerji, T. and Dvorkin, J., 2009, The rock physics handbook, Cambridge University Press

- Schoen, J.H., 2015, Physical Properties of Rocks, Elsevier

6. Abrasivity behaviour via CERCHAR test

The CERCHAR (Laboratoire du Centre d'Etudes et Recherches des Charbonnages) abrasivity test is used to determine the CERCHAR Abrasivity Index (CAI). The CAI classification according to the International Society for Rock Mechanics (ISRM) ranges from 0.1 (extremely low abrasivity) to >5.0 (extremely high abrasivity). Measurement procedure follows standard NF P 94-430-1, AFNOR Paris 2000.

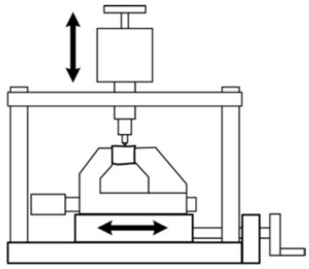


Figure 4: CERCHAR test apparatus depicting direction of weight movement (vertical) and steel pin (horizontal).

A sample's surface of a 10 mm rock piece was scratched 5 times for 1 mm/sec with a defined test pin (Rockwell hardness = HRC 54-56) along 5 different locations on the sample with a pin direction normal to the foliation on the sawn rock surface. The wear and tear of the testing pin was checked under a microscope with a computer-aided image processing program. Each individual test pin was examined 4 times at different angles (0°, 90°, 180°, 270°) and an average value was calculated. The mean total abrasion was calculated from these mean values, which were then divided by a factor of 100 to obtain the CAI.

References & further reading:

- Alber, M, Yrah, O, Dahl, F., Bruland, A., Käsling, H., Michalakopoulus, Th., Cardu, M., Hagan, P., Aydin, H., Özarslan, 2013, ISRM Suggested Method for Determining the Abrasivity of Rock by the CERCHAR Abrasivity Test, Rock Mechanics and Rock Engineering, https://doi:10.1007/s00603-013-0518-0

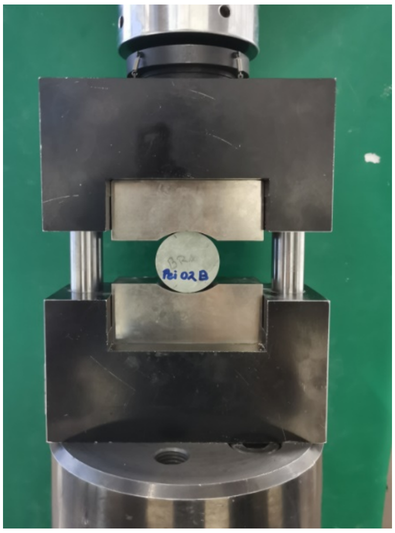
7. Tensile strength determination via Brazilian tensile test

The Brazilian tensile test is an indirect method to derive the uniaxial tensile strength of a material. A circular rock disc sample was prepared and subjected to compression between two curved platens in a servo-hydraulic rock testing system type MTS 815. During test procedure, it is assumed that the platens are rigid compared to the rock and follow a linear load distribution. This testing machine is ideal for uniaxial and triaxial compression tests as well as for direct and indirect tensile tests designed for testing rock samples up to 2850 kN axial compressive forces of up to 2850 kN and 1340 kN of tensile forces. The control mode was regulated at 3 mm/min. The uniaxial tensile strength σ_t (MPa) was calculated using the failure load F_a (kN) at which a tensile crack develops, according to:

$$\sigma_t = \frac{2F_a}{\pi D t} = 0.636 \frac{F_a}{D t}$$

With:

D = diameter (mm),
t = thickness (mm).



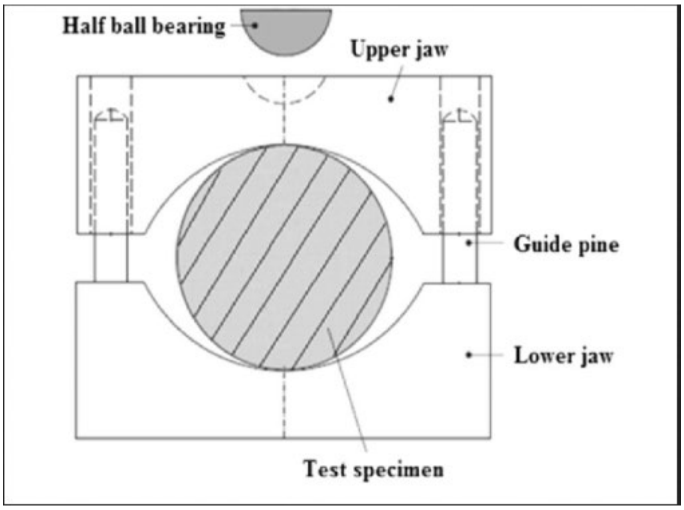


Figure 5: Brazilian testing apparatus (left) and illustration of measurement procedure (right), after Bieniawski and Hawkes, 1978.

References & further reading:

- Bieniawski, Z.T. and Hawkes, I. 1978. Suggested methods for determining tensile strength of rock materials. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 15(3): 99-103, https://doi.org/10.1016/0148-9062(78)90003-7.
- MTS Rock and Concrete Mechanics Testing System, Technical Description, MTS, Eden Prairie (USA)

8. Strength index determination via point load test

The point load strength index is determined using the point load test according to ISRM following the method after Franklin (1985). This index is further correlated with the uniaxial compressive strength (UCS). The testing device depicts the same as used for the Brazilian tensile strength test (see section 7) via a servo-hydraulic rock testing press type MTS 815, which applied an axial pressure with a control mode of 1,35 mm/min. The test specimen was clamped between two loading plates and pressure was applied until rock failure.

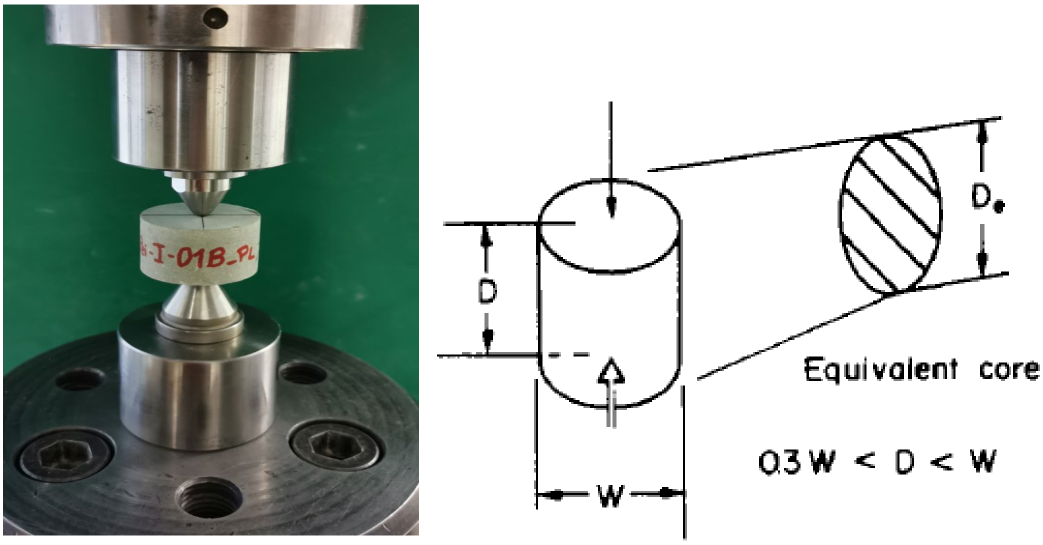


Figure 6: Point Load test (left) and schematic illustration (right) showing dimensions and direction for axial loading.

The load applied to the sample was converted to the uncorrected point load strength, I_s (MPa), according to:

$$I_S = \frac{P}{D_e^2}$$

With:
P = applied load (N),
D_e = equivalent core diameter (mm), calculated as:

$$D_e^2 = 4\,{}^{A}/_{\pi}$$

With:
A = minimum cross-sectional area (mm^2) of a plane through the platen contact points.
Finally, the corrected point load strength index (MPa) equivalent to point load index for a 50 mm diameter sample, is calculated according to:

$$I_{S(50)} = FI_S$$

With
F = unitless geometric correction factor:

$$F = \left(\frac{D_e}{50}\right)^{0.45}$$

The mean value of $I_{s(50)}$ was calculated by removing the two highest and lowest values from 10 or more valid tests. When significantly fewer results were available, only the highest and lowest results were removed, and the mean was calculated from the remaining results.
To calculate mean values, test results were grouped according to similar sample locations and lithology. This provided mean values $I_{s(50)}$ on a location and lithology basis for further correlations with UCS values (see section 10), according to:

$$\mathrm{UCS} = \mathrm{cI}_{s(50)}$$

With:
c = unitless correlation factor ranging from 20 to 25, derived by plotting UCS and $I_{s(50)}$ values for different locations and lithologies.

References & further reading:

- Franklin, J.A. 1985. Suggested method for determining point load strength. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 22(2): 51-60, https://doi.org/10.1016/0148-9062(85)92327-7.

9. Abrasivity behaviour via Laboratoire Central des Ponts et Chaussee (LCPC) test

The LCPC test is used to derive the abrasivity of rock material. Test equipment consisted of an electric motor, which uses a rotating shaft to set a rectangular metal wing with a standardized steel hardness according to HRB 60-75 in rotation. The metal wing was immersed in a gravelly material with grain sizes of 4 - 6.3 mm in a steel container. The metal wing rotated at 4500 rpm for five minutes. To determine the abrasiveness, the metal wing was weighed before and after the measurement. The weight loss of the wing is a measure of the abrasiveness of the material. For each sample run, a new metal wing was used.

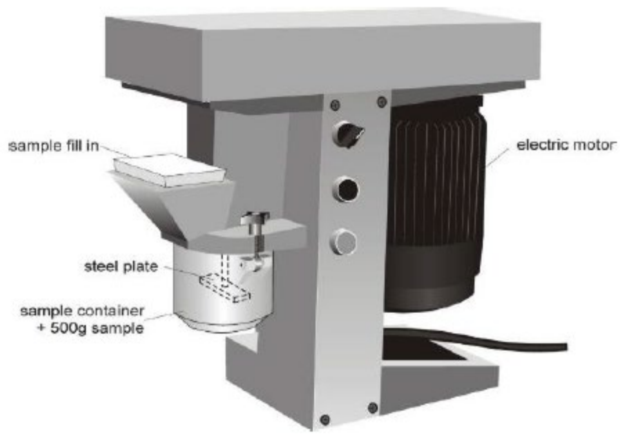


Figure 7: LCPC testing apparatus scheme as used for analysis.

10. Unconfined compressive strength via UCS test

The unconfined (sometimes also uniaxial) compressive strength (UCS) is used to measure the uniaxial rock strength of a rock sample. Cementations, i.e. bounding of solid components, anisotropy, porosity and fractures significantly influence the final results of the test.

The UCS test was carried out on a computer-controlled servo-hydraulic MTS 815 testing apparatus, with a load frame of type 315.02 and a machine rigidity of 9 MN/mm. The test specimens depicted a height-to-diameter ratio of 2:1 and were used without an intermediate layer or lubricant between the pressure plates. The upper plate was loaded with a low axial force and spherically supported. Loading up to rock failure was controlled with a rate of 0.5 mm/min. The UCS (MPa) was then calculated using the maximum force F_{max} (N) and test specimen cross-sectional area A (mm^2) according to:

Figure 8: UCS testing apparatus with rock sample during loading.

$$\mathrm{UCS} = {}^{\mathrm{F_{max}}}/_{\mathrm{A}}$$

References & further reading:

- Bieniawski, Z.T., Bernede, M.J. 1979. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Part 1. Suggested method for the determination of the uniaxial compressive strength of rock materials. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 16(2) 137-138.
- Schoen, J.H., 2015, Physical Properties of Rocks, Elsevier