Rock mass characterization for engineering design

Part 1: Physical properties of rocks

The aim of the laboratory sessions is to get familiar with three rock physical properties (transport, acoustic and electrical properties) and to examine how they are related to each other. The experiments will be performed on three different rocks: Molasse sandstone, Iragna gneiss (Ticino), and thermally cracked Iragna gneiss.

The exercise is divided into 4 stations.

- X-ray based determination of porosity and permeability;
- Ultrasonic wave measurement at room pressure and temperature;
- Electrical conductivity measurement at room pressure and temperature;
- Permeability measurement.

4 groups of 3-4 people need to be formed. Every group will spend about 2 hours per station. One assistant will be supervising each station. At the end of the semester you will have to submit one report per group.

The report should include:

- Detailed experimental procedure and a sketch of the experimental set up for each of the 4 Stations;
- Table with the results for each of the 4 stations;
- Answers to all the questions in the “Report” section of each station;
- Interpretation of the results with particular attention to the effect of the lithology on the measured property;
- Comparison between the 4 stations (i.e. physical properties) for the three different lithologies.

Part 2: Deformation of rocks

The aim of the laboratory sessions is to investigate rock deformation processes. The experiments will be performed on three different rocks: Carrara marble, Molasse sandstone and Iragna gneiss (Ticino).

The session is divided into 3 stations.

- Porosity measurement with a Helium pycnometer and Optical characterization with optical microscope;
- Uniaxial deformation;
- Triaxial deformation;
- Friction experiments.

4 groups of 3-4 people need to be formed. Every group will spend about 2 hours per station. One assistant will be supervising each station. At the end of the semester you will have to submit one report per group.

The report should include:

- Detailed experimental procedure and a sketch of the experimental set up for each of the 4 Stations;
- Table with the results for each of the 4 stations;
- Answers to all the questions in the “Report” section of each station;
- Interpretation of the results with particular attention to the deformation;
- Comparison between the 4 stations (i.e. deformation processes).

The report must not exceed 6 pages and should be sent to marie.violay@epfl.ch before the 10 of June 2025.
Report will make for 50 % of the final mark.

Elastic properties of rock samples from ultrasonic propagation

1. Scope

The aim of this laboratory session is to understand how seismic wave propagation on rock samples controls the elastic properties of the material. Compression waves and Shear waves will be pulsed through cylindrical rock samples and received at the other end. The travel times of the waves in the rock samples will allow the determination of V_P and V_S and the computation of the dynamic elastic properties of the three rocks.
The elastic properties determined through ultrasonic wave propagation (dynamic) will differ from the static elastic properties measured through laboratory tests (Uniaxial and triaxial compression for example). Ultrasonic seismic waves are generated and recorded by piezoelectric transducers (i.e. ceramic elements that oscillate when connected to an electric current (pulsing mode) or generate a current when they oscillate (receiving mode)).

2. Experimental Setup

- High-precision balance;
- Caliper;
- 6 cylindrical rock samples, 3 water saturated and 3 oven-dried (Molasse sandstone, intact and cracked gneiss);
- Clamp;
- 2 Piezoelectric P-wave transducers;
- 2 Piezoelectric S-wave transducers;
- Pulse Generator with output signal and synchronization ports;
- 4-channels oscilloscope.

3. Procedure

- Calculate the rock densities (ρ) by weighting the dry and wet samples and measuring their size with the caliper.
- Open “APS MUX configurator” (pulse generator software) and “US_EPFL_setup" (oscilloscope software, Figure 2);
- Set the pulse generator software as in Figure 3: connect to COM12, output channel 2 (check on pulse generator), 400V output voltage, input channel 2 (check on oscilloscope, Figure 3);
- By default, the oscilloscope software displays the pulse (“ch 1”), filtered and averaged to improve signal quality (Figure 4). Right-click on

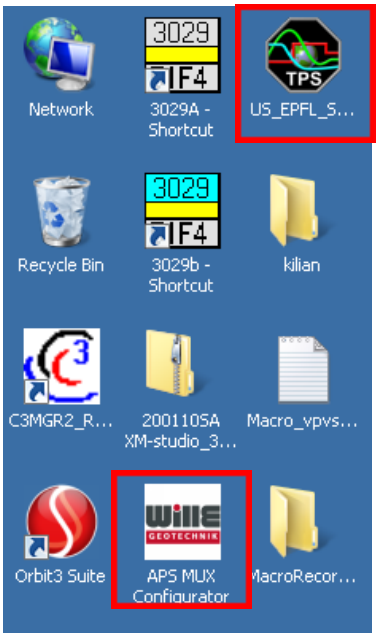


Figure 2: the two softwares to be opened are highlighted in red.

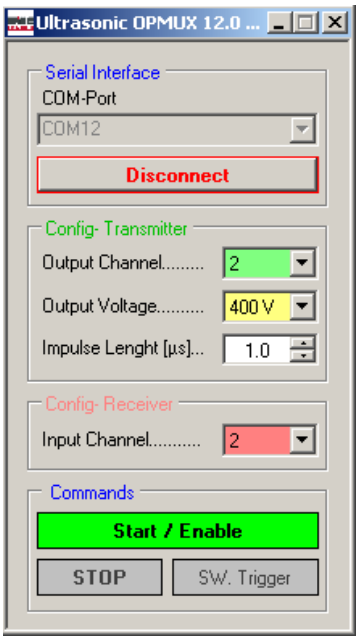


Figure 3: Settings for the pulse generator software.

"Low pass filter 1" and click on "remove all sources";

- Click and drag "Ch2" (passive receiving transducer) on "Low pass filter 1" to visualize the filtered and averaged receiver;
- Double click on "Ch1" to visualize both the pulsing and the receiving signal;
- Connect the P-wave transducers to the pulse generator and oscilloscope;
- Click on "Start/Enable" on the pulse generator software and put the transducers together to check for signal;
- If there is a signal, place the transducers in the slots at the two ends of the clamp;
- Apply some couplant at the two ends of a sample and clamp it to transmit an ultrasonic wave through it (be careful not to clamp the sandstone too hard, it can break);

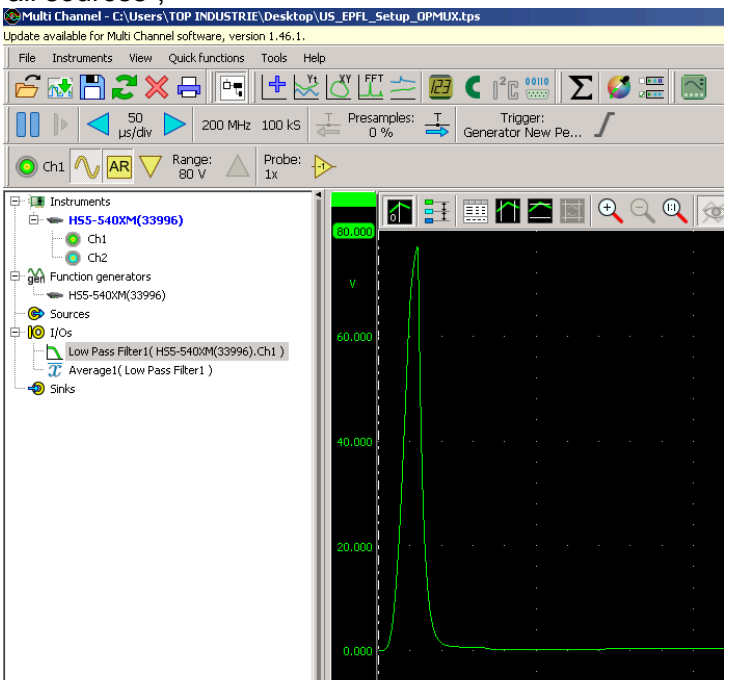


Figure 4: Oscilloscope software in default settings.

- To pick the arrival times, you can either right-click on the plot in the oscilloscope software and save the wave ("export data" be careful **NOT** to save it in .bin, use .mat or .csv) to pick the times on your laptop (slower but you can check the data at home), or
- Right click on the plot and click on "show vertical cursors" and "value window". Two white vertical bars will appear. Those can be moved on the plot to pick the start of the pulse and the first arrival of P or S wave. The times are displayed in the lower part of the "value window" and can be directly reported in the table below (faster but you cannot check/correct the values at home, Figure 5). IMPORTANT: if you use the

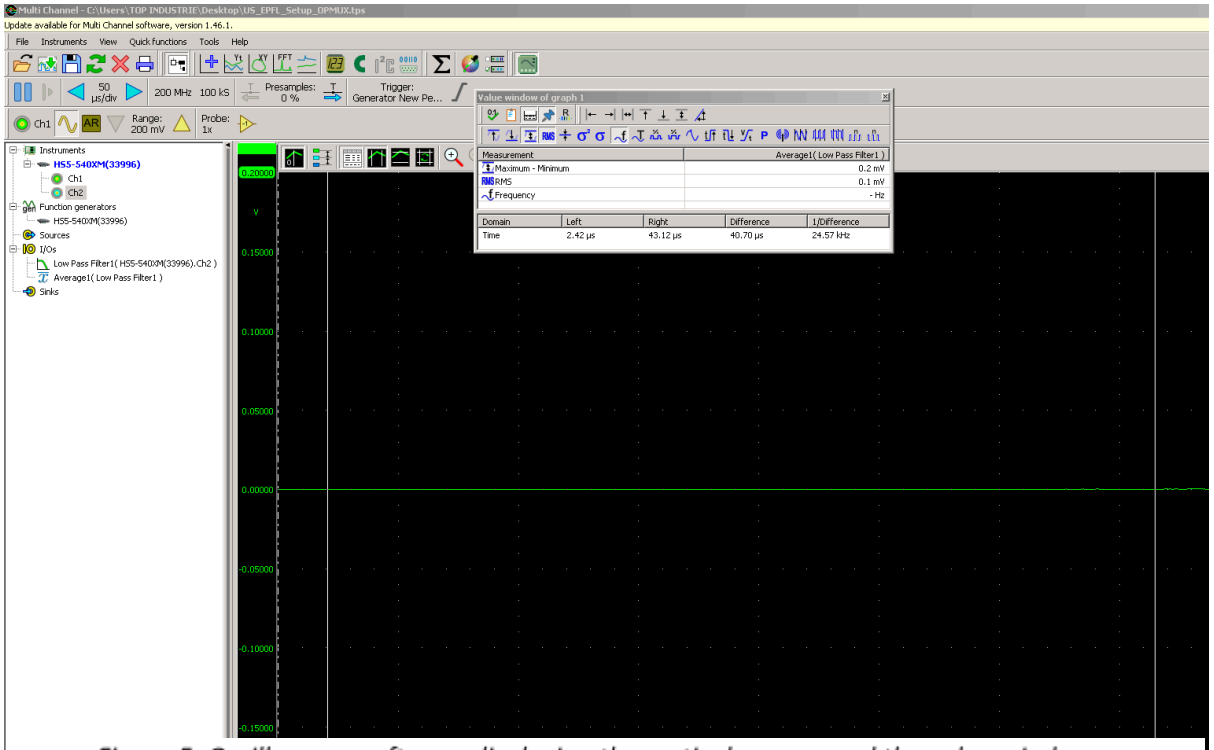


Figure 5: Oscilloscope software displaying the vertical cursors and the value window.

vertical cursors and save the waveform, only the portion within the cursors will be saved;

- Perform three measurements on each sample by unclamping and reclamping it to obtain the error of the measurement;
- Remove the sample, clean the transducers with a paper towel and repeat the measure for the other samples. Be sure not to leave the saturated samples outside the solution when you are finished.

4. Report

The following parts should be included in the report for the ultrasonic waves propagation part:

- Detailed experimental procedure with a diagram of the experimental setup, the steps followed for measuring elastic wave propagation in the rock samples, a quick diagram of the observed waves in the oscilloscope;
- Table with arrival times from oscilloscope measurements with estimated uncertainties for the measurement;
- Calculation of V_P and V_S for the different experimental with standard deviation;
- Computation of the following dynamic elastic constants using only V_P, V_S and ρ (kg/m3):
  - E = Youngs modulus of elasticity (Pa);
  - v = Poissons ratio;
  - μ = modulus of rigidity or shear modulus (Pa);
  - K = bulk modulus (Pa);
  - λ = Lame's coefficient;
  - M= P-wave modulus.
- Interpretation of the results with respect to the observed experimental samples;
- Through microstructures observation and porosity/permeability analyses explain the differences in measured wave velocities.

	Dry			Wet		
Sample	Molasse sandstone	Intact gneiss	Cracked gneiss	Molasse sandstone	Intact gneiss	Cracked gneiss
Length						
Diameter						
Weight						
Density (ρ)						
t_P 1						
t_P 2						
t_P 3						
v_P 1						
v_P 2						
v_P 3						
mean v_P						
v_P std. dev.						
t_S 1						
t_S 2						
t_S 3						
v_S 1						
v_S 2						
v_S 3						
mean v_S						
v_S std. dev.						

Electrical conductivity measurement at room pressure and temperature

1. Scope

The aim of this laboratory session is to learn how to prepare samples for and measure electrical conductivity of different rocks, linking the electrical properties of rocks to porosity and saturating fluid salinity.

The measurement is performed placing two electrodes at both sides of rock samples. An alternating electric current with different frequencies is transmitted through one electrode and received by the electrode on the other side of the sample. To avoid measuring the current flowing on the side of the sample, a guard ring is placed around the electrodes to ground the current flowing on the surface of the sample.

Electrical conductivity in frequency is a complex value, it can be described either with its modulus and phase or with real and imaginary components. (Figure 6). For the scope of this laboratory session, only the conductivity at the lowest phase (ideally 0°, when real conductivity=modulus of conductivity) will be considered.

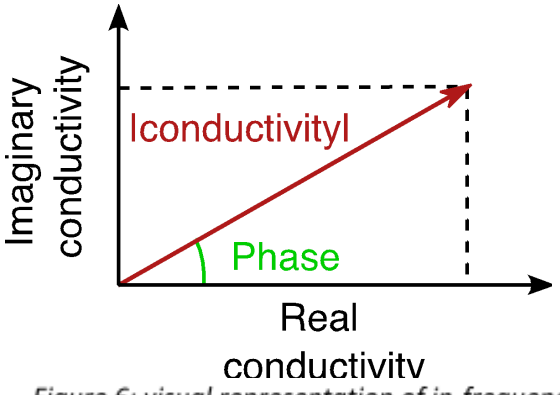


Figure 6: visual representation of in-frequency electrical conductivity.

2. Experimental Material

- NaCl;
- Precision electronic scale;
- Deionized water;
- Fluid conductivity meter;
- 2 electrodes with guard rings with 4 coaxial cables.
- Acquisition apparatus connected to the computer, able to measure electrical impedance over a wide frequency band (Solartron XM modulab impedancemeter);
- 18 cylindrical rock samples, 6 for each of the three rock types tested: Molasse sandstone, intact and cracked gneiss;
- 5 saturating fluids with different salinity:
    - Solution 1: Deionized water,
    - Solution 2: 2g/L of NaCl dissolved in deionized water,
    - Solution 3: 5g/L of NaCl dissolved in deionized water,
    - Solution 4: 10g/L of NaCl dissolved in deionized water,

- Solution 5: 35g/L of NaCl dissolved in deionized water.

3. Procedure

- Prepare 1l of 10 g/l of NaCl solution;
- Since the samples need to stay in the solution for at least three weeks to allow for electrolitic equilibration, you will measure samples that were prepared beforehand;
- Measure the electrical conductivity of all the saturating solutions with the fluid conductivity meter;
- Measure the size of the electrodes;
- Launch “XM-studio MTS” on the desktop;
- Create a new project (“File” -> “new project”);
- Define the type of waveform to impose across your sample: “Step” -> “voltage controlled impedance” -> “Constant level“ (Figure 7);
- Set the following parameters in the “impedance setup” tab: “amplitude” 5 V, “start frequency” 1 MHz, “end frequency” 1Hz (Figure 8);
- On the “Setup” menu in the “instrument experiment setup” select “Connectors”->”4 terminals”(Figure 9);
- Measure the length and diameter of the sample to be tested;
- Place a sample between the electrodes, making sure that the electrode does not stick out from the sides of the samples;
- Click on “Run”, rename the experiment based on which rock and salinity are being tested and click on “Run” again (Figure 10);
- The data will be plotted in a |Z| versus F (Impedance vs frequency) and θ versus F (phase vs frequency) plot;
- Once the measure is finished, click on the folder with the name of the experiment and then “export all” to save a .csv file with all the data (Figure 11);

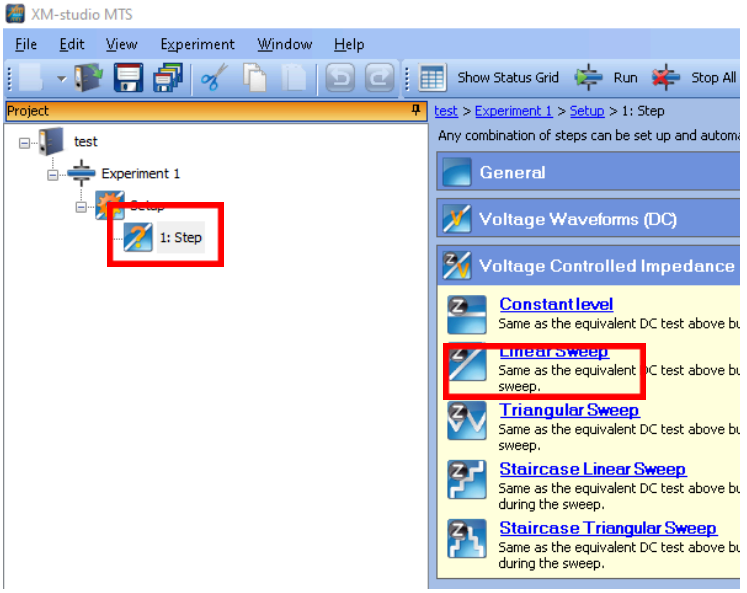


Figure 7: XM- studio MTS launch interface

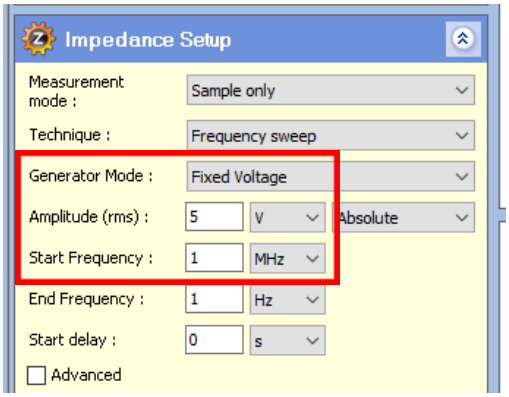


Figure 8: Impedance parameters

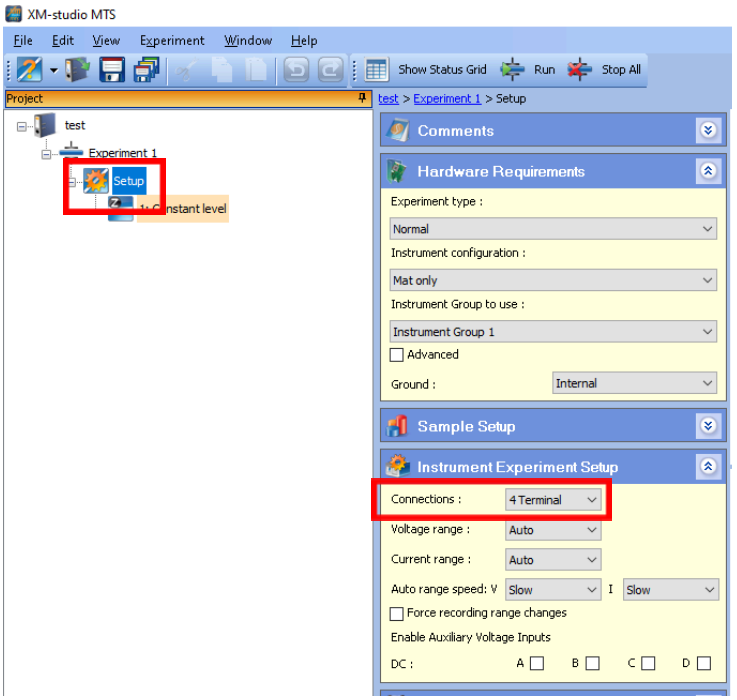


Figure 9: Connection setup

- Remove the sample and clean the electrodes with a paper towel;
- Repeat for the three rocks and all the salinities. Do not leave the samples outside of the saturating solution after measuring and do not mix samples with different salinities.

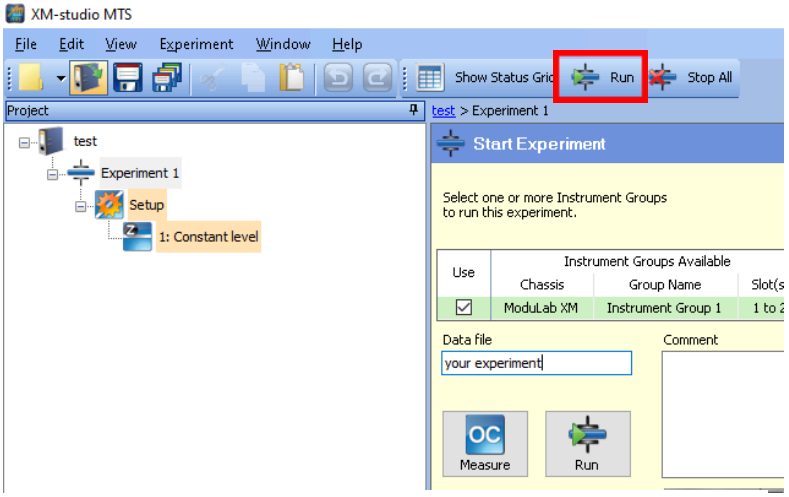


Figure 10: running the experiment

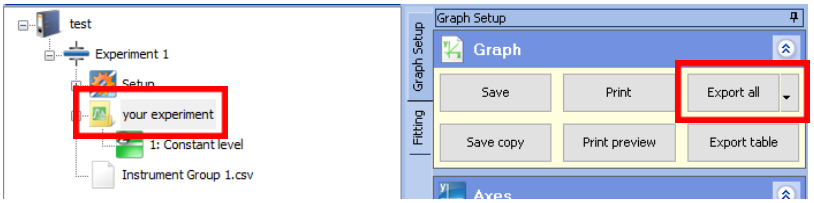


Figure 11: Exporting the data

4. Report

For this part of the report, all the information (rocks, fluids, length, electrical resistance and resistivity at the lowest phase, frequency at the lowest phase, formation factor) has to be arranged in a table and the following questions have to be addressed:

- How and why does electrical conductivity correlate with the fluid salinity? How do the measurements with deionized water saturation compare to the other solutions and why?
- For one chosen rock sample, investigate the frequency dependence of the electrical conductivity measured. Often, in brine-saturated rocks, the frequency of 1 kHz is chosen, why?
- The impedance meter measures the electrical impedance Z (Ω, equivalent to R in DC) of the sample. For each sample, calculate the electrical conductivity (S/ m) and plot it versus saturating fluid conductivity (think carefully about the surface over which the current is flowing).
- Distilled water has an electrical conductivity S = 0.055 $\mu S/cm$. The electrical conductivity of a fluid is a function of the ions nature (l_i in S $\cdot$ m^2/mol) and its concentration (c_i in mol /L) such that S = $c_1 * l_1 + c_2 * l_2$. Calculate the electrical conductivity of solutions 1, 2 and 3. Assuming that water ion concentration is only made up of dissolved NaCl, what could you conclude about the salinity of the deionized water the samples were saturated in?
  NB: At 25°C, l_{Na^+} = 5.0 $mS \cdot m^2/mol$ and l_{Cl^-} = 7.63 $mS \cdot m^2/mol$.
- Determine the formation factor for each rock type using:
  - the deionized water-saturated samples only;
  - all the salinities combined.

  Report the different formation factors in a table and compare them.
- Plot the measured formation factors as a function of the samples P-wave velocity, porosity and permeability. Can one obtain correlations between formation factor and those three properties? Why?

Porosity of Rocks

1. Scope

Methods for measuring porosity in rocks include

1. Direct methods;

2.Indirect Methods.

The aim of this laboratory session is to compute the porosity of 3 different rocks using an indirect method. In particular, in order to define the porosity of a rock we need to measure the bulk volume and the matrix volume.

Bulk Volume

The determination of the bulk volume can be done in two different ways:

1. Linear measurements;
2. Displacement methods.

In this lab session we will measure the bulk volume of our samples using linear measurements.

Matrix volume

In order to establish the porosity of our rock, the matrix of the rock will be measured with the gas displacement method, based on Boyle's law.

In our pycnometer, Helium is used as the displacement medium. The sample is sealed in the sample chamber of known volume and the system is vacuumed. Then, the gas is introduced in the sample chamber and then expanded into a calibrated expansion chamber (Figure 1). The pressures measured upon filling the sample chamber and the sample chamber + expansion chamber allow for the calculation of the sample solid phase volume. Helium molecules rapidly fill pores as small as one angstrom in diameter, only the solid phase of the sample displaces the gas.

Matrix volume is then calculated by the instrument as follows:

$$V_{matrix} = V_{samp\ chamber} - \frac{V_{exp}}{\frac{P_1}{P_2} - 1}$$

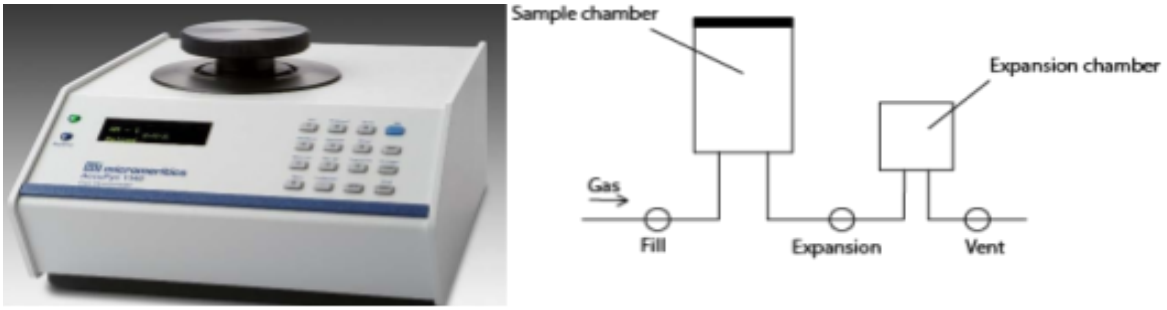


Figure 1: Pycnometer AccuPyc III 1340 and an schematic view of the pycnometer componens

2. Experimental setup

You will use the following material:

- 3 rock samples: molasse sandstone, intact and cracked gneiss;
- Pycnometer AccuPyc III 1340;
- Caliper.

3. Procedure

For each sample:

- Measure the bulk volume;
- Remove the top cap of the pycnometer;
- Extract the sample chamber holder with gloves;
- Insert the sample in the holder and close the cap;
- Start the analysis (blue button on the keypad-> “Analyze”);
- No need to input the sample mass (press “enter”);
- Chamber insert: none(“enter” if none is displayed, otherwise press choice until “none” appears);
- The analysis takes around 15 minutes
- To visualize the results, press “choice” until the mean and standard deviation are visualized;
- Compute the porosity.

Rock	Length	Diameter	V_{bulk}	V_{matrix}	ΔV_{matrix}	Porosity
Molasse sandstone						
Gneiss intact						
Gneiss cracked						

4. Report

For the porosity laboratory part, you need to report:

- Porosity for the different rocks, expliciting the main value and the standard deviation of the porosity;
- Compare and comment on the porosity of the intact and cracked gneiss.

Polarized microscope

1. Scope

The aim of this laboratory session is to have a quick introduction to rock observation at the microscope. This allows us to study the mineralogy, texture and porosity of a rock. To achieve this, a thin section of the rock is made (30 µm thick), and placed in the microscope.

The microscopes used are equipped with two polarizers: one to polarize the light before it crosses the thin section and a second one to polarize the light after it crosses the thin section (analyzer). Thin sections can be observed in two modes:

- Polarized non analyzed light, to observe mineral colors, shape, rock texture and porosity;
- polarized and analyzed light, to observe interference colors ("*teinte de polarisation*" in french, an optical property of minerals), can be used to observe porosity.

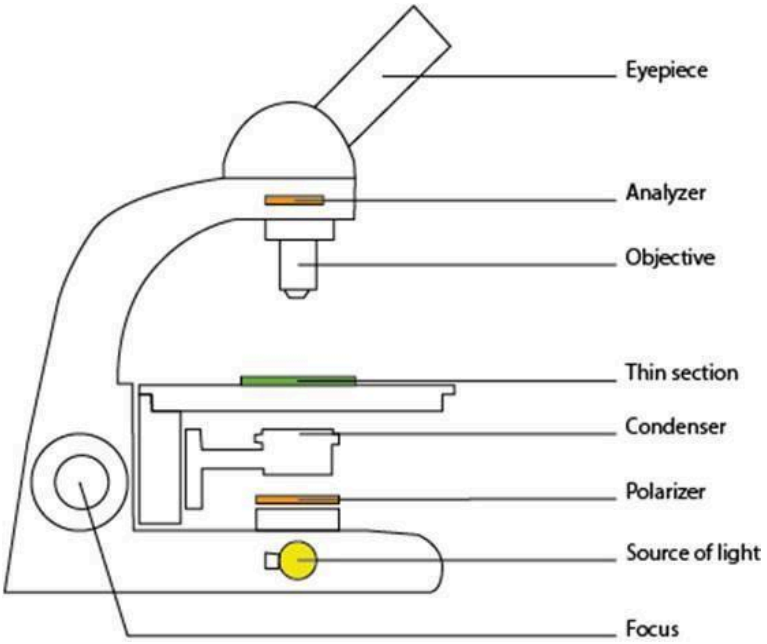


Figure 12: Sketch of the polarized microscope

2. Experimental Material

- Polarized microscope
- Three thin sections: Molasse sandstone, intact granite from Italy (porosity comparable to the Iragna gneiss), the same granite thermally cracked at 650°C.

3. Procedure

The following sequence will allow you to use the polarized light microscope.

- Switch the light on;
- Adjust the light and bring the condenser roughly halfway up;
- Check if polarizer and analyser are at 90° (turning the analyzer on, you should see complete black through the eyepieces);
- Turn the analyzer off;
- Select the smallest magnification lens;
- Place the thin section on the rotating plate;
- Focus by moving up the objective.

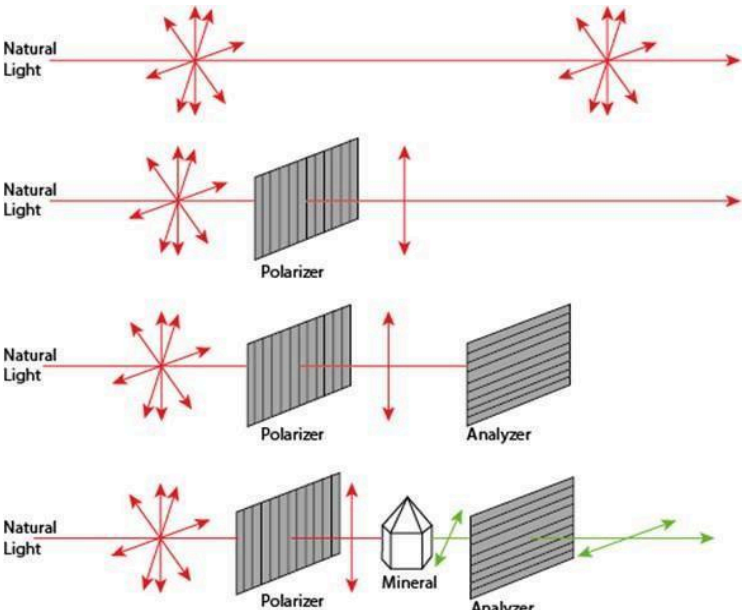


Figure 13: Light path through a polarized microscope

- The total magnification and field of view (FOV, i.e. the real size of the diameter of the view through the eyepiece) is reported in the table below:

Ocular lens	10x	10x	10x	10x
Objective lens	1x	5x	10x	40x
Total Magnification	10x	50x	100x	400x
FOV (mm)	20	4	2	0.5

Identify minerals contained in sandstone and granite (See mineral identification table). Identify the porosity and what are the differences between a sandstone, an intact and a cracked granite.

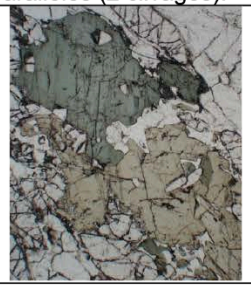
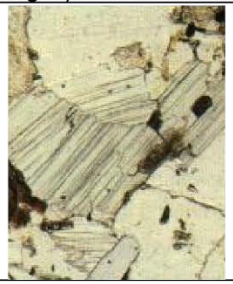
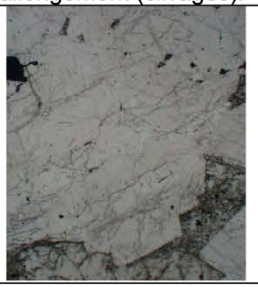
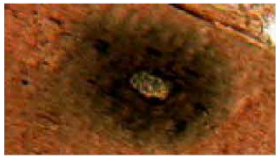
4. Report

The report for the optical microscopy part should include:

- A hand-drawn sketch for each of the three observed rocks that is well representative of the rock (remember to put a scale);
- Elaborate on the differences in porosity between sandstone, intact and cracked granite.

PLANCHE D'IDENTIFICATION AU MICROSCOPE DE MINERAUX DES ROCHES GRANITIQUES

NB : Les lames minces peuvent être observées, à l'œil nu, sur fond blanc ce qui permet de repérer certains minéraux colorés avant d'utiliser le microscope.

		AMPHIBOLES	MICAS		QUARTZ	FELDSPATHS	
		Hornblende	**Muscovite**	**Biotite**	**Quartz**	**Orthose**	**Plagioclases**
MICROSCOPE POLARISANT	**En LPNA**	Minéral brun-verdâtre, dont la couleur varie en fonction de l'orientation. Deux séries de fissures parallèles (2 clivages).	Minéral incolore, limpide, souvent en baguettes allongées. Fines fissures parallèles très nettes (clivages).	Minéral brun foncé à beige dont la couleur varie avec l'orientation. Fines fissures parallèles dans le sens de la longueur (clivages).	Minéral incolore très limpide.	Minéral incolore avec nombreuses impuretés lui donnant un aspect sale.	Minéral incolore. Présence de fissures parallèles perpendiculaires à l'allongement (clivages).
							
	$n LPA	Teintes vives de polarisation : rouge, magenta, bleu, vert, très atténuées par la couleur naturelle du minéral.	Teintes de polarisation & jaune, rose ou magenta très vives.	Teintes vives de polarisation : rouge, magenta, bleu, vert, jaune, très atténuées par la couleur naturelle.	Teinte de polarisation: gris clair à blanc.	Teintes de polarisation : gris plus ou moins foncé. Marbrures (présence de deux moitiés de cristal de teintes différentes.	Teintes de polarisation : gris plus ou moins clairs répartis en bandes parallèles (macle polysynthétique).
							
					**Zircon parfois en inclusion dans la Biotite** zircon reconnaissable à une auréole sombre due à sa radioactivité qui altère la Biotite. Teintes vives en LPA. *Ici vu à fort grossissement.*		

Permeability

1. Scope

The aim of this laboratory session is to learn how to measure permeability of rock samples using a gas permeameter.

Permeability is calculated with Darcy's law:

$$k = \frac{\mu L Q P_d}{A P_m (P_u - P_d)}$$

Where k is the permeability, μ is the viscosity of the gas, L is the length of the sample, Q is the gas flow, A is the sample area, P_u is the upstream pore fluid pressure, P_d is the downstream pore fluid pressure, and P_m is the mean pore fluid pressure across the sample. This formulation of Darcy's law accounts for the use of a compressible pore fluid.

Permeability measured with gas might differ from the real permeability because of gas slippage on the pore/crack surfaces (Klinkenberg effect) and needs to be corrected.

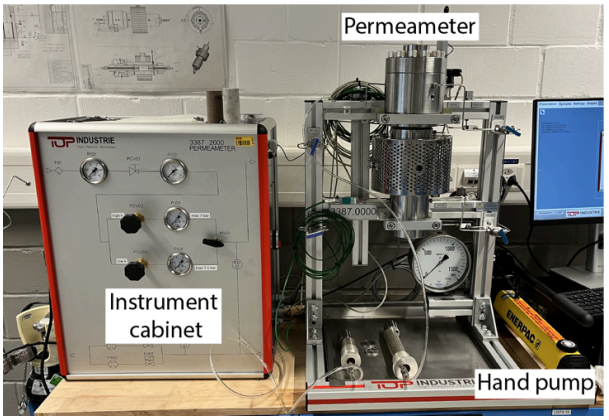
Apparent and real permeability are related following:

$$k_g = k_L\left(1 - \frac{b}{P_m}\right)$$

Where k_g is the apparent gas permeability, k_L is the real permeability, b is the Klinkenberg's factor and P_m is the mean pressure of the gas in the sample.

2. Experimental material

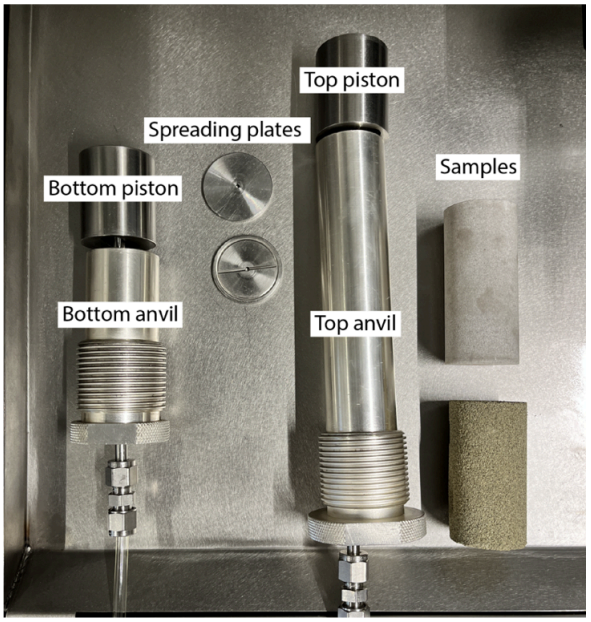
- High pressure/high temperature permeameter with valve and electrical cabinet
- Top anvil and piston;
- Bottom anvil and piston;
- 2 spreading plates;
- Teflon extractor;
- 3 samples: molasse sandstone, intact and cracked gneiss.



3. Procedure

To operate the permeameter, you need to follow these steps:

- Make sure the software is properly communicating with the permeameter (green lights on FT 01, FT 02 and TE 01 in the bottom status bar);
- Go on the synoptic tab (top toolbar), press "zero adjustment" and "start zero setting" to calibrate all the sensors on atmospheric conditions;
- When the calibration is finished, press "validate calibration";
- Now the sample assembly can be mounted.



- Place a spreader plate on the bottom piston, with the grooves facing the sample surface;
- On top of the plate, place one of the samples and another spreader plate (grooves facing the sample)
- Carefully insert the whole assembly in the permeameter from the bottom and screw the anvil in until the end of the thread;
- Screw the top anvil and piston on the top of the permeameter. Based on the length of the sample the top anvil will stick out a bit, it needs to be tightened by hand, not excessively hard.
- Get familiar with the diagram drawn on the cabinet on the left (the assistant will guide you through the schematic of the machine);
- Open MV01 and MV03 to apply confinement pressure and axial pressure (Pc and Pax), check that MV 02 and MV 04 are closed.
- Use the manual pump (slowly) to increase the pressure up to 50 bar
- Check the pressure on the pressure transducers in the software (PT 01 confinement and PT 02 axial);
- Close MV 01 and MV 03;
- Go on the graphs tab and wait until the pressure is stable. If the pressure decreases too, much repeat the pressure increase process;
- Ask the assistant to open the gas bottle for you;
- Check that the gas pressure on PI01 is below 50 bars and on PI02 is 7 bars;
- Based on the permeability of your sample, open either PCV 02 (low permeability, >10-16 m2) or PCV 03 (low permeability, <10-16 m2);
- Turn MV 01 so that the arrow on the handle is facing the used flowpath;
- Apply the desired pressure differential by tuning wither PCV 02 or PCV 03 (start from a high dP and reduce it until you get a good flow reading);
- Check on the software in the synoptic tab whether the pressure and the flow stabilize after some time (blue and green light blinking below the graph on the right);
- When the flow is stable, note down the flow value (in green on the left, on the side of the flowmeter pictograms) and the pressure difference (PD01);
- Repeat the measurement for 5 different ΔP;
- Slowly open MV02 and MV04 to release Pc and Pax, check that the pressure is at 0 bar;
- Unscrew the top anvil and remove it together with the piston;
- Slowly unscrew the bottom anvil taking care not to have the sample assembly fall down on the bench;
- If the sample assembly does not come out by itself, gently push the sample out by inserting the teflon extractor from the top;
- Repeat the measurement for the 3 different rocks.

4. Report

Calculating permeability using Darcy's law:

For each sample, plot Q/A versus ΔP/L. Do the data reflect Darcian fluid flow? If yes, calculate the sample permeability using this plot. For each sample, calculate the permeability of the sample at every ΔP (k_g) using Darcy's law.

Checking for a Klinkenberg effect:

Check whether there is a Klinkenberg effect by plotting the calculated permeability at every ΔP (k_g) versus 1/P_m (P_m is the mean gas pressure in the sample).

Comment on the differences in permeability between the rocks and the presence/absence of a Klinkenberg effect. If you have identified a sample with a Klinkenberg effect, explain the microstructural controls that have caused this effect.

Triaxial deformation

1. Scope

The aim of this laboratory session is to learn how to perform and interpret a triaxial experiment with a conventional triaxial cell (Hoek cell), investigating the pressure dependance on the strength of the three investigated rocks.

The experiments will be performed on Molasse sandstone, intact and thermally cracked gneiss at three confining pressures of X, Y, Z MPa.

2. Experimental material

- Walter + Bai hydraulic press (maximum load 2 MN), equipped with:
  - Load cell;
  - Two linear opto - electronic transducers (displacement transducers);
- Press control unit;
- 38 mm Hoek triaxial cell;
- Piston with hemispherical seat;
- Syringe pump for confinement pressure;
- 38 mm diameter Carrara marble sample.

3. Procedure

- Measure the size of the sample;
- Insert the sample in the Hoek cell;
- Place the cell in the hydraulic press;
- Insert the piston with the hemispherical seat in the cell;
  - Following the instructions of the assistant, apply a confinement pressure of XYZ MPa;
- Deform the sample with a strain rate of 5×10^{-5} s^{-1} (0.24 mm/min) up to around 5% strain;

4. Report

For this part of the laboratory experiments the following items should be included in the report:

- Detailed experimental procedure with a diagram of how the experiment was mounted and the precise steps followed for performing the laboratory test.
- Stress-strain curve for the three confinement pressures (correct the displacement for the stiffness of the apparatus, which is 5 GN/mm), including comments on the different parts of the curve and the differences between experiments.
- Comments on the pressure dependance of the strength of the three rocks.
- Calculation of Young's modulus (E) for all the experiments.

Uniaxial compression test

1. Scope

The aim of this laboratory session is to learn how to perform a Uniaxial compressive strength (UCS) test: the ultimate stress a cylindrical rock specimen can hold under axial load.
It is the most important mechanical property of rock material, used in design, analysis and modelling. From a UCS experiment, elastic properties of the rock can be determined as well.

Figure : Shimadzu mechanical press

2. Experimental material

- Shimadzu mechanical press (maximum load 100 kN), fitted with:
  - Integrated load cell;
  - Integrated position transducer;
- Press control unit
- Extensometer to measure radial deformation;
- 2 radial chains to be fitted around the samples to measure radial deformation;
- 20 mm diameter intact gneiss sample;
- 20 mm diameter thermally cracked gneiss sample;
- 38 mm diameter Molasse sandstone sample.

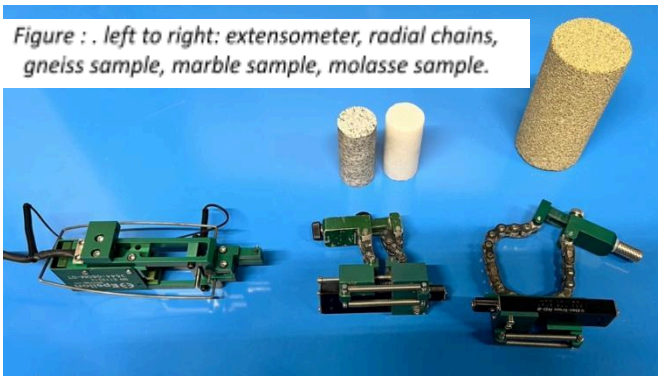


Figure : . left to right: extensometer, radial chains, gneiss sample, marble sample, molasse sample.

3. Procedure

- Place the extensometer chain around one of the three samples, placing it at half of the height of the sample;
- Place the extensometer in the extensometer chain (Figure 4);
- Position the sample in the press, being careful to place it in the middle of the plates and that the extensometer is resting on the support bar (Figure 5);
- Turn on the press;
- Zero the force sensor (top right on the control panel);
- Lower the press head until the sample is held firmly by the plate using the controller on the machine (Jog on/off -> high speed -> arrow down);
- Lower the safety glass of the press;
- Zero the position transducer (“stroke” button on top right on the control panel);
- Turn on TRAPEZIUMX-V on the computer (user name and password: admin);


Figure : extensometer placement on the chain.

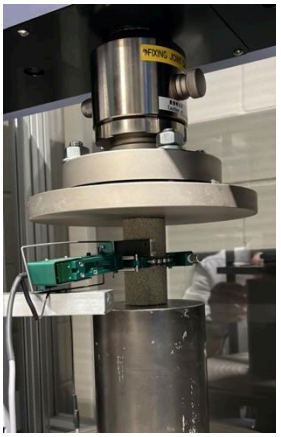


Figure : sample and extensometer placement.

- Press on “select method and start test”;
- Use the method “UCS 0.24” for 20 mm samples and “UCS 0.48” for 38 mm samples. In both cases, the strain rate will be 10^{-4} s^{-1}. When starting the procedure, the press will move down (loading the sample) at the imposed speed. When pushing a key on the keyboard (DO NOT press the spacebar as it stops the test), the press will move up at twice the imposed speed (unloading the sample); pressing a key a second time will resume sample loading. The loading-unloading-reloading cycle is performed in the elastic domain, it needs to be started roughly halfway through the elastic loading of the rock.
- Click on “start test” to begin the experiment;
- Perform the unloading-reloading once the sample has deformed elastically for some time (need to guess if the UCS is not known).
- Once the sample fails, stop the experiment, raise the press head and remove the sample.
- Repeat the procedure for the three samples.

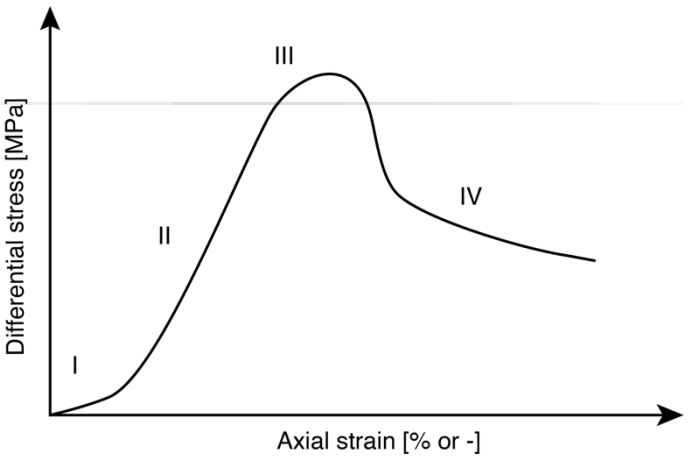
Stiffness correction:

The machine deform proportionally to the force that it applies to the sample. To get the real deformation of the rock sample, a correction must be applied.
The stiffness is non-linear between 0 and 0.15 mm of displacement, and follows:
$d=(3F+784)^{0.5}/900-7/225$,
where d is the displacement and F is the force applied by the press. Above 0.15 mm of displacement, instead, the machine deforms linearly following:
$d=F/101000+331/5050$.

4. Report

For this part of the laboratory the following items should be included in the report:

- Detailed experimental procedure with a diagram of how the experiment was mounted and the precise steps followed for performing the laboratory test.
- Stress-strain (axial and lateral) curves for the tested materials and detailed comments on each phase of the uniaxial cycle (Figure 6), stressing the differences between rocks.
- Calculation of the uniaxial strength of each rock and comments.
- Calculation of Young’s modulus and Poisson’s ratio.
- Comparison of the static elastic moduli measured through uni-axial compression with the moduli determined by ultrasonic measurements.
- Through microstructures observation and porosity analyses explain the differences in compressive strength and axial and radial strain evolution.



Measuring Rock Friction

1. Objective:

The aim of this experimental protocol is to enhance your comprehension of discontinuity mechanical behavior. By conducting direct shear friction experiments on rock gouge using the HighSteps machine, you will evaluate the frictional strength of the gouge under different normal stresses. The focus of this experiment is on measuring the frictional peak force. By conducting multiple normal stress steps and retrieving the frictional force at which failure occurs, the ultimate goal is to build a failure envelope.

2. Background:

During your bachelor's studies, you learned about the importance of discontinuities in rock masses. These discontinuities are pivotal in rock mechanics and are influenced by factors such as peak friction angle, dilatation angle, cohesion, and normal stress. Reactivation of joints (the force required to initiate sliding) is governed by various factors, including peak friction angle, dilatation angle, and cohesion at low normal stress, while at high normal stress, it is primarily influenced by the peak friction angle, akin to static friction coefficient. This concept is encapsulated in the Barton Law.

In this laboratory session we learn how to measure friction of rock samples using a double direct shear apparatus.

In the absence of cohesion, friction (μ) can be calculated directly by dividing the shear stress (τ) by the normal stress (σ) applied on a frictional surface:

$\mu = \tau/\sigma$

Stresses acting on a surface are calculated by dividing the force (F) applied on the plane by the nominal contact area (A) of this plane. In this case, the area A of each gouge layer is 3.4 cm * 3.4 cm.

3. Experimental procedure

1. Experimental material

- Double shear apparatus;
- User manual;
- Metallic holders for gouge samples;
- Spatulas, rulers, tape, and metallic blocks for gouge installation;
- Gouge from Carrara marble (grains diameter < 125 μm)

2. Setup:

Here we learn how to use the HighSteps machine, a biaxial shear machine, for direct shear friction experiments (Karin will assist). A user guide with all the steps needed for sample preparation is provided. The basic steps are the following:

- Select Carrara Marble gouge as the test material (grains diameter < 125 μm).
- Prepare the sample following the guidelines from the user's manual.
- Insert the sample into the machine.
- Set target normal stresses of 10 MPa , 20 MPa and 30 MPa. For each normal stress step, apply a vertical piston displacement velocity of 30 μm/s. Each normal stress step should be maintained until the sample fails. Then, click to the next step in the procedure.

3. Direct Shear Experiments:

The experiment should be set so that we can measure the frictional strength of the gouge during failure and observe changes with increasing normal forces.

The goal is to:

- Conduct direct shear friction experiments at a constant shear velocity.
- Identify, record and determine the frictional force required to initiate slip (peak frictional force).
- Perform multiple normal stress steps to determine frictional force at failure and construct a failure envelope.

4. Data Collection:

- Record horizontal and vertical forces applied by the machine, as well as horizontal and vertical displacements of the pistons during the experiments . The data is recorded in a .tdms file. Use the script extract_forces_displacements_from_tdms_to_csv_for_students.py to convert it to csv. You can use the .csv to process/plot the data. Note that the time vector contains only the time increment between each point, it needs to be converted in order to plot your data versus time.
- As the displacements are not measured directly on the sample's boundaries and the pistons have an elastic behavior with given stiffness (see fig. 1), displacements have to be corrected. Considering the conditions applied, what should be the correction to be applied to the horizontal displacements measured (estimate it from fig. 1a). Is the raw displacement measured larger or smaller than the one applied on the sample (after correction)?
- Calculate normal and shear stress τ. Is τ = vertical force / A or τ = vertical force / 2A? Why?
- Plot the ratio of shear stress to normal stress versus time, and versus slip.

5. Analysis:

- For each normal force step, calculate the peak shear stress from the data.
- Construct a failure envelope based on the recorded data. When plotting peak shear stress versus normal stress, fit a linear regression, and find the friction coefficient which corresponds to the slope. Is there any cohesion?

6. Comparison and Discussion:

- Compare experimental measurements of friction values with existing literature.
- Highlight the limitations of the experiments in understanding joint mechanical behavior.
- Are the conditions applied (shear stress and normal stress) comparable to nature?

4. Report:

Provide a comprehensive analysis and interpretation of experimental data, including the determination of the failure envelope and friction coefficient of the rock tested. Discuss the implications of the findings and their relevance to rock mechanics research.

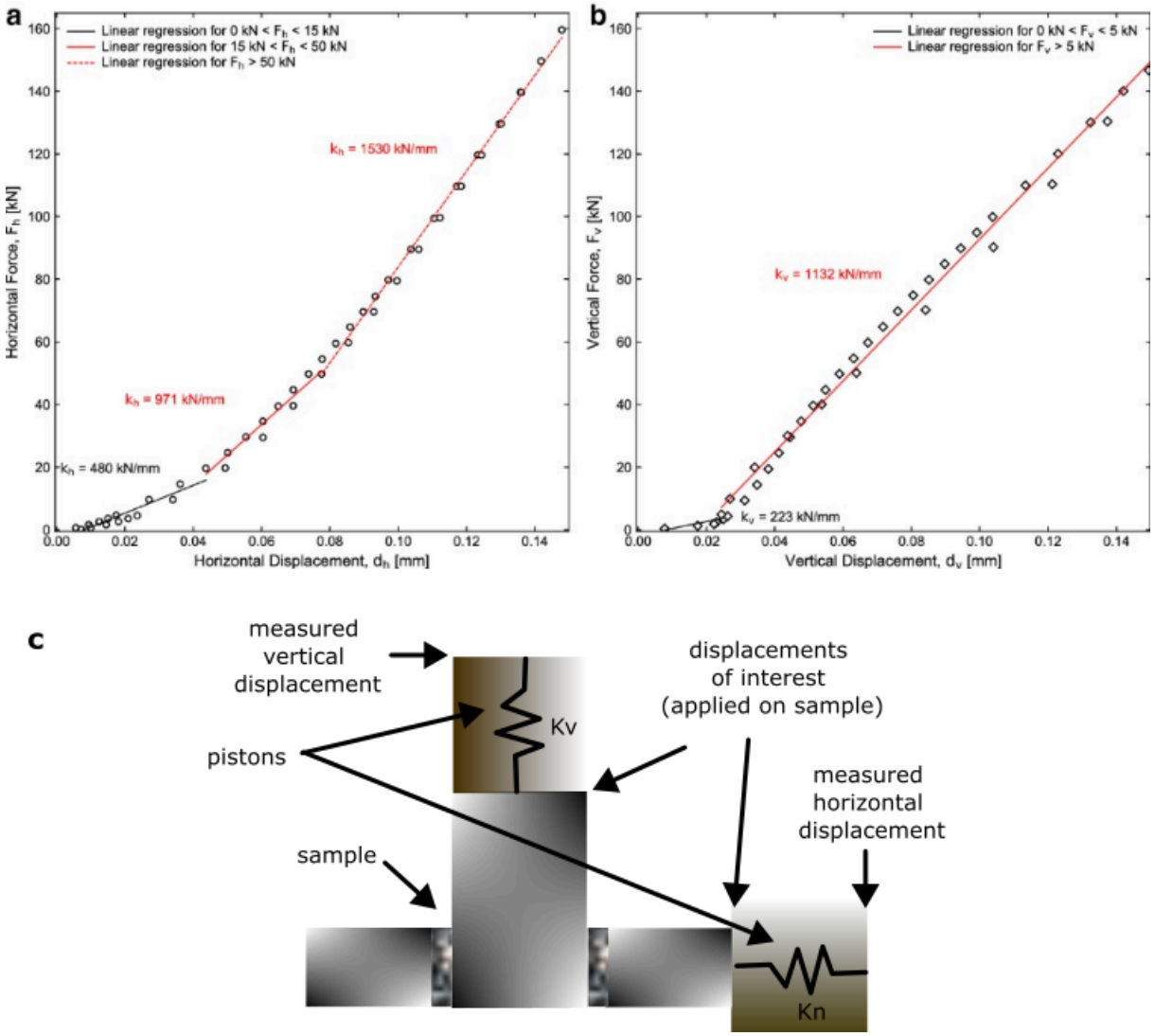


Figure 7: Correction of machine stiffness. Forces versus displacements curves in graphs a) and b) are measured using completely rigid metallic samples. Displacements measured for given forces are therefore accommodated by the pistons ((a) horizontal and (b) vertical). During experiments, we have to correct for the compliance of the pistons in order to measure what is applied on a real sample as in c).

Some guidelines for the report

A scientific report is a structured document that presents findings in a clear, concise, and logical manner. The writing should be objective, using precise language and avoiding unnecessary details. Each section serves a specific purpose, helping to communicate your study effectively. In the context of the course, the extension of the report should be limited to 6 pages.

Sections a report should include

1. Introduction

This section provides background information on the experience and explains the purpose of the study. The introduction sets the stage for why the research was conducted. Be as precise as possible considering the limit of 6 pages.

2. Methods

Also known as "Materials and Methods," this section describes how the study was conducted. It includes the experimental setup, materials used, procedures followed, and how data were collected and analyzed. Make sure to be as precise as possible considering the limit of 6 pages.

3. Results

The findings of your research are presented here by including tables, graphs, and figures to illustrate collected data clearly. Avoid discussing the implications of the results in this section.

4. Discussion

Compare the results of the different rock types tested and how the experimental conditions affected them. Explain why these differences matter. For example, how does increasing a certain variable change the results? Why is a specific physical property important?. Use the course slides on moodle to find equations to support your findings. You may also address unexpected results. Answer in this section the questions of each station.

5. Conclusions

This final section summarizes the key findings and their implications. The main points are shown concisely while highlighting the importance of the report. Avoid introducing new information here.