Prepared in cooperation with the École Polytechnique Fédérale de Lausanne, National Park Service, and Université de Lausanne

Rock Strength Properties of Granitic Rocks in Yosemite Valley, Yosemite National Park, California

Data Series 1126

U.S. Department of the Interior
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Cover. Photograph of El Capitan in western Yosemite Valley. The central part of the cliff is 900 meters tall. The southeast face of El Capitan, on the right side of the cliff, exposes eight different granitic rock units. Photograph by Greg Stock.

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By Brian D. Collins, Federica Sandrone, Laurent Gastaldo, Greg M. Stock, and
Michel Jaboyedoff

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Datum Information

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) and projected to Universal Transverse Mercator (UTM) Zone 11S (northern hemisphere) coordinates in metric units.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) in metric units. Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations and Symbols

cm	centimeters
CB	chevron bend
CCNBD	cracked chevron notched Brazilian disk
CMOD	crack mouth opening displacement
EPFL	École Polytechnique Fédérale de Lausanne
GPa	gigapascals
kN	kilonewtons
LPD	load point displacement
LVDT	linear variable differential transformer
Ma	mega-annums
mm	millimeters
MPa	megapascals
$MPa \cdot m^{1/2}$	megapascal square root meter
NPS	National Park Service
PVC	polyvinyl chloride
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
//	parallel
$\perp$	perpendicular

Notation

α	failure angle
B	disk thickness
D	diameter
c_{peak}	peak cohesion
c_{res}	residual cohesion
E_{50}	elastic modulus at 50 percent strain
H	height
K_{CB}	mode I fracture toughness for chevron bend samples
K_{IC}	mode I fracture toughness for cracked chevron notched Brazilian disk samples
L	length
ν	Poisson's ratio
P	axial load
ϕ_{peak}	peak friction angle
ϕ_{res}	residual friction angle
σ_1	normal stress
σ_3	confinement stress
σ_c	unconfined compressive strength
σ_t	tensile stress
Y^*_{min}	critical dimensionless stress intensity factor

Rock Strength Properties of Granitic Rocks in Yosemite Valley, Yosemite National Park, California

By Brian D. Collins,[1] Federica Sandrone,[2] Laurent Gastaldo,[2] Greg M. Stock,[3] and Michel Jaboyedoff[4]

Introduction

Yosemite National Park, located in the central part of California's Sierra Nevada mountains, is a glacially carved landscape filled with iconic rock formations, such as Cathedral Peak, El Capitan, and Half Dome. Igneous rocks, consisting primarily of variations of granite, granodiorite, and tonalite, make up the majority of the bedrock geology (Calkins and others, 1985; Huber and others, 1989; Peck, 2002; Putnam and others, 2014) and their overall strength supports the spectacular cliffs and domes of Yosemite Valley that draw many visitors to the park (fig. 1). These same sheer cliffs also are the source areas for frequent rock falls (fig. 2), which, in addition to being the primary mechanism for cliff formation, can also pose a hazard to visitors and infrastructure located below (Stock and others, 2013). To obtain rock strength parameters for use in assessing rock-fall potential in Yosemite National Park, we conducted a comprehensive rock mechanics laboratory testing program on a set of granitic rocks that form many of the cliffs in Yosemite Valley.

The geomorphological signature of rock falls in Yosemite Valley is clearly evident by the accumulation of rock debris (talus) at the base of nearly all of Yosemite's cliffs (for example, Wieczorek and Jäger, 1996). Recent studies show that a rock fall occurs somewhere in Yosemite at a frequency of approximately once per week, with the majority occurring in wilderness and other undeveloped areas of Yosemite Valley (Stock and others, 2013). However, rock falls have also

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Figure 1. Photograph of eastern Yosemite Valley as seen from the summit of Eagle Peak. Half Dome, in the center background, rises nearly 1,500 meters above the floor of Yosemite Valley. Photograph by Greg M. Stock, National Park Service.

caused fatalities and injuries, damaged infrastructure, and led to road closures that can ensnarl traffic and greatly reduce or completely block emergency access. The U.S. Geological Survey (USGS), working collaboratively with the National Park Service (NPS), has conducted numerous studies on rock-fall hazards in Yosemite, with a primary focus on rock falls occurring in Yosemite Valley, where the cliffs rise more than 1,000 meters above the valley floor (fig. 1) and where the vast majority of visitors congregate. In addition to comprehensive studies of rock-fall hazard and risk (for example, Wieczorek and others, 1998, 1999, 2008; Guzzetti and others, 2003; Stock and others, 2014; Matasci and others, 2018), detailed studies of characteristic rock falls (for example, Wieczorek and Snyder, 1999; Wieczorek and others, 2000; Stock and others, 2012, Zimmer and others, 2012), and those occurring from specific triggering mechanisms (for example, Collins and Stock, 2016) have been conducted to better understand the hazards presented by rock falls in the park. These and ongoing studies require a suite of technical resources, including high-resolution topography (for example, Collins and Stock, 2012; Stock and others, 2012; Matasci and others, 2018), photography (for example, Stock and others, 2011; Guerin and others, 2019), historical records (for example, Stock and others, 2013), and an understanding of triggering conditions (that is, meteorology and climatology, seismicity, and other factors; for example, Wieczorek and Jäger, 1996; Stock and others, 2013).

Figure 2. Photograph of a 9,811-cubic-meter rock fall from the southeast face of El Capitan on September 28, 2017. Photograph by Hennette Olsboe Foreyen, used with permission.

Despite the progress in understanding rock-fall triggering in Yosemite, several potentially significant influences remain understudied. One such influence is the role that material strength (that is, rock properties) plays in controlling rock fracture. Rock strength parameters (for example, compressive strength, tensile strength, and fracture toughness) describe the propensity for individual rock types to fracture (break) in particular ways and from particular loading mechanisms (fig. 3). For example, a section of rock cliff loaded vertically (that is, from only the mass of rock above it) and absent of any internal joints or fractures, might undergo primarily compressive loading (fig. 3*A*), in which the uniaxial unconfined compressive strength of the rock would govern its stability. Rocks may also fail in shear (sliding), for example, when a block of rock is subject to multiaxial loading (fig. 3*B*). In this case, the shear strength may govern the rock mass stability. Triaxial testing conditions, in which a cylindrical sample is laterally confined prior to axial compressive loading, is one way to induce shear stress conditions in rock to obtain a measure of shear strength. A cliff with a roof section may undergo direct tensile forces across the rock mass, in which case the rock is loaded in tension (fig. 3*C*), and a measure of tensile strength would be needed to properly analyze the rock fall triggering mechanism. Finally, rock may break under fracture conditions (either from tension, shear, or both), such that fracture toughness strength parameters are needed to assess stability. These conditions might be met, for example, as a result of the opening of a fracture (fig. 3*D*) from internal water pressure, thermal expansion (Collins and Stock, 2016), or failure of a rock bridge (for example, Guerin and others, 2019). Using quantitative values of rock strength parameters can vastly improve the ability to assess the likelihood of future rock falls with analytical models (for example, Matasci and others, 2018; Guerin and others, 2019).

Rock strength parameters are typically measured in laboratory settings (Ulusay, 2015), although in situ methods are also quite common for site-specific projects. Laboratory testing offers the ability to conduct testing under carefully controlled conditions with instrumentation that can precisely measure the forces (stresses) applied to, and the resulting deformation (strains) of, rock samples. Cylinders of rock cored from larger collected samples are generally used in laboratory mechanical strength tests. Both the test procedures and the proper analysis of the resulting data typically require the use of cylindrical test samples. Although rock strength parameters taken from small samples are not necessarily representative of the rock mass strength (the term “rock mass” denoting a large volume of rock with existing fractures), rock strength values (that is, for characterization of intact rock at the small, sample-size scale) provide requisite data for determining rock mass strength (at the large, cliff-size scale; for example, Bieniawski, 1989).

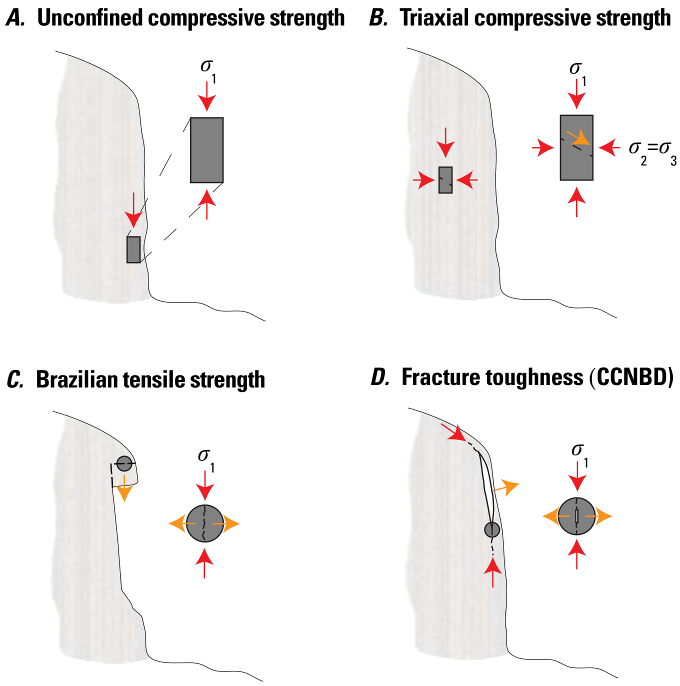


Figure 3. Schematic diagrams showing loading mechanisms for rocks exposed in cliffs. Red arrows show sense of compressive loading and orange arrows show sense of shear or tensile motion. Stresses are labeled as the major (σ_1) and minor (σ_2=σ_3) principal compressive stresses. Types of associated rock mechanics testing are shown in dark gray. *A*, Unconfined compressive loading occurs when a rock is loaded along only one axis. *B*, Triaxial loading occurs when a rock is confined in two orthogonal directions, and is loaded in a third direction, orthogonal to the first two, thereby inducing shear stress within the sample. *C*, Tensile loading occurs as rock is pulled apart, here shown as gravity loading on a roof. Note that the Brazilian tensile strength test is an indirect method to measure tensile strength, obtained by compressive loading orthogonal to the minor (tensile) principal stress direction. Note that the sample orientation has been rotated by 90 degrees compared to the schematic diagram of the cliff. *D*, Fracture loading occurs when a rock experiences tension and (or) shear along existing fractures as a result of the loading conditions (here shown for the cracked chevron notched Brazilian disk sample [CCNBD] as compression along an opening, leading to orthogonal tension at the fracture surface).

The study presented herein provides rock strength parameters of granitic rocks from Yosemite National Park obtained by rock mechanics laboratory methods. We conducted unconfined compressive strength, triaxial shear strength, Brazilian tensile strength (an indirect measure of tensile strength), and mode I (tensile opening) fracture toughness testing on bulk samples of six igneous rock units that represent the primary rock types exposed in many of Yosemite Valley's cliffs. These types of tests provide the parameters needed to conduct a wide variety of rock mechanics analyses related to rock-fall initiation of Yosemite's cliffs (for example, Collins and Stock, 2016; Matasci and others, 2018; Guerin and others, 2019).

Study Area Background

The bedrock of Yosemite National Park is composed primarily of granitic rocks associated with the Sierra Nevada batholith (Huber and others, 1989; Bateman, 1992). These rocks were intruded into metamorphic, sedimentary, and volcanic country rocks during subduction of the Farallon Plate beneath the North American Plate from approximately 120 to 85 million years ago (Ma) (Huber, 1987; Huber and others, 1989; Coleman and others, 2004). Granitic rocks in Yosemite range in composition from diorite and gabbro to leucogranite, but are predominantly granodiorite, tonalite, and granite (Calkins and others, 1985; Peck, 2002).

In Yosemite Valley, granitic rocks are part of the intrusive suites of Yosemite Valley and Buena Vista Crest and the Tuolumne Intrusive Suite (fig. 4; Bateman, 1992; Ratajeski and others, 2001; Peck, 2002). The western half of Yosemite Valley is composed predominantly of middle Cretaceous (around 100 Ma) granitic rocks associated with the intrusive suites of Yosemite Valley and Buena Vista Crest (Bateman, 1992; Ratajeski and others, 2001; Peck, 2002). In the eastern half of Yosemite Valley, rocks of the intrusive suite of Yosemite Valley are intruded by Late Cretaceous (95 to 85 Ma) granodiorites and granites associated with the Tuolumne Intrusive Suite (Bateman, 1992; Peck, 2002; Coleman and others, 2004). The cliffs west of Yosemite Valley, within the Merced River gorge, are composed of Early Cretaceous (124 to 105 Ma) granodiorites and tonalites associated with the Fine Gold Intrusive Suite (fig. 4; Peck, 2002; Lackey and others, 2012). Some of the iconic formations of Yosemite Valley are composed of a single rock type (for example, Half Dome, which is composed exclusively of Half Dome Granodiorite), whereas others are composed of many different rock types (for example, the southeast face of El Capitan—see cover image, which exposes eight different granitic rock types ranging from diorite to granite; Putnam and others, 2014, 2015; Ratajeski and others, 2001).

Pleistocene glacial advances, the most recent of which ended about 15,000 years ago (see Wahrhaftig and others, 2019, and references therein), modified the Pliocene topography of Yosemite Valley, deepening and widening the valley, and ultimately leaving behind steep cliffs with spectacularly exposed bedrock. Subsequent rock falls have further sculpted the cliffs and deposited the resulting rock debris in talus piles at the base of the cliffs (Wieczorek and Jäger, 1996). Lithologic diversity of boulders within these talus piles thus reflects the lithologic diversity of the cliffs from which they derived (for example, Stock and Uhrhammer, 2010), and offers an accessible means of sampling the rocks that form the cliffs.

Rock Units Tested

We investigated strength properties of six granitic rock units in Yosemite Valley (table 1), representing the bedrock that forms many of the iconic formations in Yosemite Valley. Here we provide brief summaries of each tested rock unit, following the descriptions of Peck (2002) and Putnam and others (2014). Further details can be found in a number of reports and maps (for example, Calkins and others, 1985; Bateman, 1992; Ratajeski and others, 2001; Coleman and others, 2004; Putnam and others, 2015).

Taft Granite

The Taft Granite (unit Kt) is a light-colored, medium- to fine-grained granite. It is principally located in the eastern part of the intrusive suite of Yosemite Valley, and occurs in several small masses that cut the El Capitan Granite, extending south from El Capitan to Taft Point (fig. 4). Biotite averages about 3 percent by volume and is the only mafic mineral present. The Taft Granite grades locally into biotite granodiorite and biotite tonalite against contacts with the El Capitan Granite. Uranium-lead (U-Pb) radiometric ages indicate an emplacement age for the Taft Granite of 107–106 Ma (Putnam and others, 2015).

Tonalite of the Gray Bands

The tonalite of the Gray Bands (unit Kgb) is a medium to dark gray, medium- to fine-grained, biotite-rich and hornblende-poor tonalite. It is exposed as an isolated intrusion on El Capitan striking east-southeast and dipping steeply to the south. Some parts of the tonalite of the Gray Bands show localized indications of fabric, expressed by mineralogical orientations with approximately 40° dip (as measured from horizontal) to the southwest (R. Putnam, written commun., 2014). Although no age data exist, the tonalite of the Gray Bands is inferred to be approximately 107–105 Ma based on relations with adjacent units (Putnam and others, 2015).

El Capitan Granite

The El Capitan Granite (unit Kec) is a light-gray, medium- to coarse-grained granite. It is commonly porphyritic, containing phenocrysts of potassium feldspar as long as 2 centimeters (cm); plagioclase is more abundant as smaller crystals. Biotite typically composes 10 percent by volume and locally defines a weak magmatic foliation. Hornblende is either absent or present only in trace amounts. The El Capitan Granite is the principal unit of the intrusive suite of Yosemite Valley, with a surface area of approximately 600 square kilometers (Putnam and others, 2014). Within the study area, the El Capitan Granite is exposed in large swaths throughout western Yosemite Valley, extending approximately from Yosemite Falls in the east to the informally named “Cookie cliff” in the west (fig. 4) and includes a large part of El Capitan (cover image), which is the type locality for this rock. U-Pb ages indicate an emplacement age for the El Capitan Granite of 106 Ma (Putnam and others, 2015).

Diorite of North America

The diorite of North America (unit Kd) is a dark-gray to black, fine- to medium-grained biotite hornblende gabbro and diorite exposed on the southeast face of El Capitan, where it crops out in two southeast-striking, nearly vertical dike and enclave swarms (Putnam and others, 2014) that resemble a map of North America. Peck (2002) previously mapped these dikes as unit Kid and Putnam and others (2015) mapped them as unit Kd. U-Pb ages indicate an emplacement age for the diorite of North America of 104 Ma (Putnam and others, 2014, 2015). The diorite of North America is part of a larger intrusive quartz diorite unit exposed discontinuously in western Yosemite Valley that has been mapped by Peck (2002) as unit KJd (fig. 4).

Table 1. Yosemite Valley cliff rock units used in rock mechanics testing.

[Ma, million years ago]

Geologic unit symbol	Rock unit	Approx. age (Ma)	Age source
Kt	Taft Granite[1]	107–106	Putnam and others (2014, 2015)
Kgb	Tonalite of the Gray Bands[2]	107–105	Based on interpretation by Putnam and others (2015)
Kec	El Capitan Granite[1]	106	Putnam and others (2014, 2015)
Kd	Diorite of North America[3]	104	Putnam and others (2014, 2015)
Ks	Sentinel Granodiorite[1]	94	Peck (2002)
Khd	Half Dome Granodiorite[1]	92–88	Coleman and others (2004)

[1]From Peck (2002).

[2]From Putnam and others (2014, 2015).

[3]From Ratajeski and others (2001).

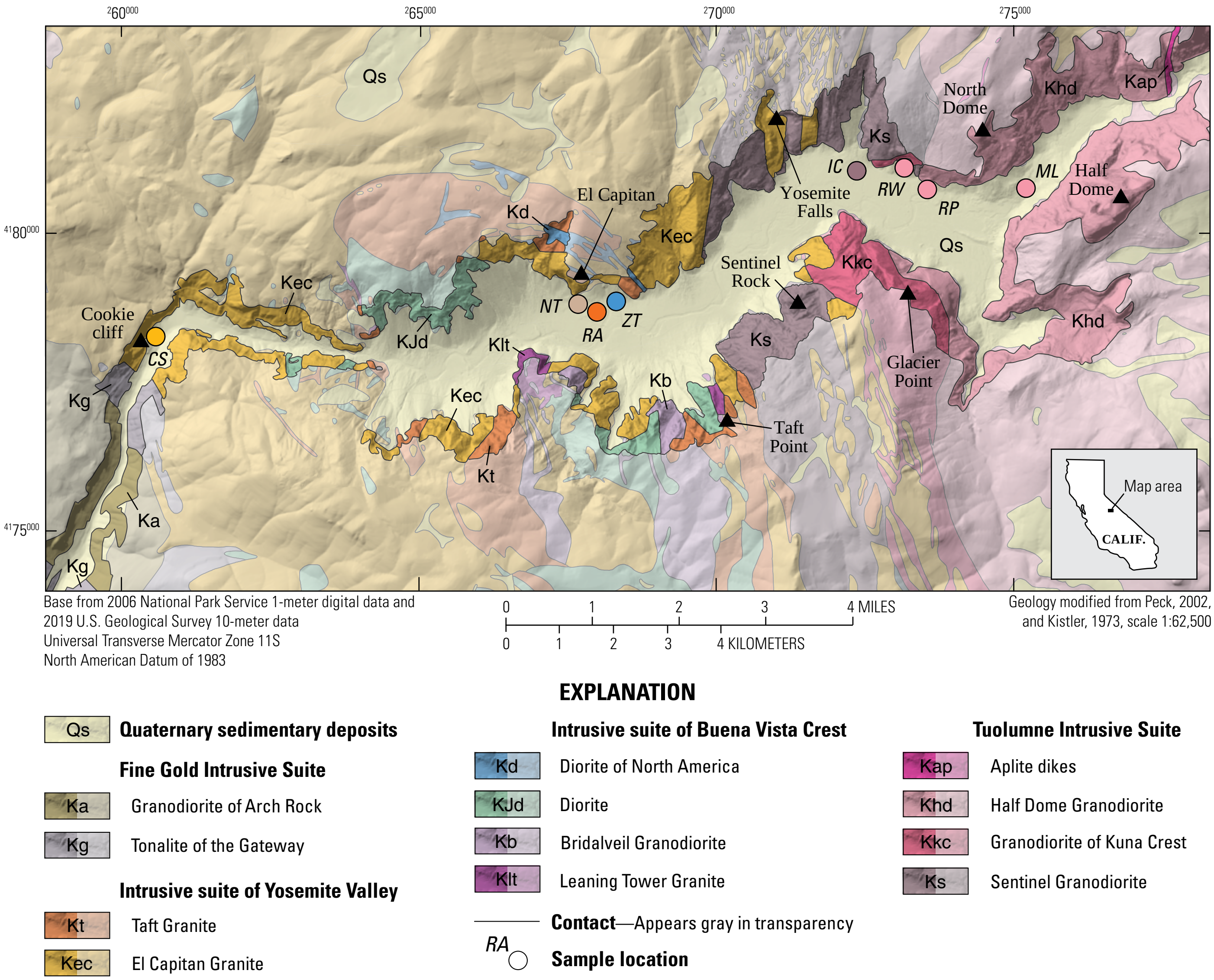


Figure 4. Map of Yosemite Valley in the central Sierra Nevada range, California, showing the distribution of the major geologic units (modified slightly from Peck, 2002, and Kistler, 1973) and locations of samples collected for rock strength testing. Exposures of the major rock units on the cliffs of Yosemite Valley are shown in bold colors; elsewhere, they are shown in transparency. Minor rock units, such as the tonalite of the Gray Bands (unit Kgb), exposed only in small outcrops on the southeast face of El Capitan (Putnam and others, 2014), are not shown. Not all rock units shown were tested. The diorite of North America (unit Kd) sampled from location "ZT" and tested herein is one of several units that make up the diorite of the intrusive suite of Buena Vista Crest (mapped as diorite, unit KJd). Sample locations for the six rock units tested are: CS, Cookie Cliff rock slide (unit Kec); NT, El Capitan Nose talus (unit Kgb); RA, El Capitan Meadow rock avalanche (unit Kt); ZT, El Capitan Zodiac talus (unit Kd); IC, Indian Creek (unit Ks); RW, Rhombus Wall (unit Khd); RP, Royal Prerogative Flake (unit Khd); and ML, Mirror Lake (unit Khd). Note that Half Dome Granodiorite (unit Khd) samples were collected from three separate locations. Grid coordinates are referenced to Universal Transverse Mercator (UTM) Zone 11S (northern hemisphere), in meters. Map modified from one originally created by Lauren Austin, National Park Service.

Sentinel Granodiorite

The Sentinel Granodiorite (unit Ks) is a medium-grained, equigranular rock with well-formed crystals of hornblende and biotite (Calkins and others, 1985; Bateman, 1992; Peck, 2002). Part of the Tuolumne Intrusive Suite, it crops out in cliffs on both the north and south sides of Yosemite Valley (fig. 4). Sentinel Rock is composed entirely of Sentinel Granodiorite and is the type locality for this unit (Bateman, 1992). The Sentinel Granodiorite shows visible foliation via the alignment of 2–5 millimeter (mm) biotite grains. In the field and near to the rim of Yosemite Valley, this is expressed through vertical to near-vertical (dipping >80° to the west) oriented foliation visible in outcrops (Peck, 2002). The age of the Sentinel Granodiorite is approximately 94 Ma (Peck, 2002).

Half Dome Granodiorite

The Half Dome Granodiorite (unit Khd) is a light-colored, medium-grained, equigranular granodiorite and granite, typically containing 8–12 percent euhedral crystals of biotite, hornblende, and titanite that are 5–10 mm across. Part of the Tuolumne Intrusive Suite, the Half Dome Granodiorite composes much of the exposed bedrock in eastern Yosemite Valley (fig. 4), including Half Dome (fig. 1), which is the type locality for this rock unit (Bateman, 1992). U-Pb ages indicate an emplacement age for the Half Dome Granodiorite of 92–88 Ma (Coleman and others, 2004).

Methods

This project was performed in cooperation with academic partners at the École Polytechnique Fédérale de Lausanne (EPFL) and Université de Lausanne, both located in Lausanne, Switzerland. All sample preparation and testing was conducted at the Laboratory of Experimental Rock Mechanics at EPFL.

Sample Collection

We collected block-sized (approximately 30 cm by 30 cm by 20 cm) bulk samples of six rock units from the talus slopes beneath the cliffs that form Yosemite Valley and surroundings (figs. 4, 5*A*; tables 2, 3). We sampled only fresh talus blocks to minimize the influences of weathering on the results. We identified samples by rock unit, location, and number (fig. 5*B*), before packing and shipping them (fig. 5*C*) to the EPFL rock mechanics laboratory in Switzerland. Although testing blocks of talus collected from beneath cliffs does not necessarily provide the maximum in situ rock strength owing to potential weakening from fall-induced impact and pre-rock-fall weathering, the blocks are still representative of the overall rock strength given that they are the surviving products of the impact. Thus, the effects of major fractures and joints that might affect rock strength are minimized, since it is presumed that the rock blocks would have already failed along these fractures at the time of rock fall and subsequent impact. Directly coring (drilling into) the cliffs themselves would be preferable for replicating the maximum likely rock strength, but we did not pursue this option given the wilderness nature of the environment in which the cliffs are located.

Sample Preparation

We prepared our bulk rock samples for testing by coring cylindrical and disk-shaped samples using a fixed-type coring machine with diamond core bits. All coring was conducted using plain water. We selected the diameter of our cores to meet the criteria (Swiss National Standard VSS–70353A; Swiss Association of Road and Transportation Experts, 2019a) that the diameter must be six to ten times larger than the maximum grain size of the rock unit used in testing; table 4), while also allowing a sufficient number of cores to be extracted from the bulk block samples. During coring of samples, we made sure to limit the maximum grain size in each core to less than or equal to 9 mm. Although a cylindrical size of 55 mm meets this criteria in all cases, it is sometimes preferable to have a slightly larger diameter sample for ease in testing. As a result, we chose a standard coring diameter of 55 mm for all tests that used cylindrical samples (unconfined compression, triaxial, and chevron bend fracture toughness) and chose a slightly larger coring diameter (80 mm) for all tests that utilized disk samples (Brazilian tensile and cracked chevron notched Brazilian disk fracture toughness).

Most of the rocks selected for testing showed little to no visual signs of anisotropy in the bulk samples, suggesting that their respective rock strength properties might be independent of loading direction. However, some igneous rocks types in Yosemite exhibit preexisting fabric (layering and [or] foliation). For example, in Yosemite Valley, the Sentinel Granodiorite (unit Ks) shows consistent steep (mostly vertical and typically greater than 80°) west-dipping foliation (Peck,

Figure 5. Photographs showing bulk rock sampling, identification, and transportation. *A*, Rock samples were collected from talus slopes that form the base of cliffs in Yosemite Valley and surrounding areas. *B*, Samples were identified with rock unit, location, and specimen number. Shown here is El Capitan Granite (unit Kec); the block is the fourth sample collected from the Cookie Cliff rock slide (sample CS4). *C*, Samples were then packed for overseas transport in a wood crate with a variety of foam padding.

Table 2. Bulk rock sample location information.

[m, meters]

General location[1]	Bulk sample numbers	Easting[2] (m)	Northing[2] (m)	Elevation[3] (m)
El Capitan Granite (unit Kec)				
Cookie Cliff rock slide	CS1, CS2, CS3, CS4	260506	4178013	1,044
Tonalite of the Gray Bands (unit Kgb)				
El Capitan Nose talus	NT1, NT2, NT3	267609	4178873	1,240
Taft Granite (unit Kt)				
El Capitan Meadow rock avalanche	RA1, RA2, RA3, RA4	267899	4178716	1,219
Diorite of North America (unit Kd)				
El Capitan Zodiac talus	ZT1, ZT2, ZT3, ZT4	268288	4178980	1,266
Sentinel Granodiorite (unit Ks)				
Indian Creek	IC1, IC2, IC3, IC4, IC5	272395	4181040	1,227
Half Dome Granodiorite (unit Khd)				
Rhombus Wall talus	RW1	273282	4181181	1,401
Royal Prerogative Flake cliff talus	RP1, RP2	273443	4180884	1,248
Royal Prerogative Flake cliff base	RP3	273421	4180890	1,233
Royal Prerogative Flake trail	RP4	273393	4180848	1,221
Mirror Lake Road	ML1, ML2, ML3	275264	4180709	1,244

[1]Place names reference common cliff and valley floor landmarks in Yosemite Valley (for example, see Reid, 1998).

[2]Northing and easting are referenced to North American Datum of 1983 (NAD 83), Universal Transverse Mercator (UTM) Zone 11S (northern hemisphere).

[3]Elevation is referenced to North American Vertical Datum of 1988 (NAVD 88).

Table 3. Bulk rock sample number, dimensions, and type of tests performed.

[cm, centimeters; cm^3, cubic centimeters; //, parallel; ⊥, perpendicular]

Bulk sample number	Length (cm)	Width (cm)	Height (cm)	Approx. volume (cm^3)	Type of test[1,2]							
					UCS	TRX	BTS		FT-CB		FT-CCNBD	
							//	⊥	//	⊥	//	⊥
El Capitan Granite (unit Kec)												
Kec-CS1	37	33	27	33,000	X	X						
Kec-CS2	47	35	36	59,200			X	X		X	X	X
Kec-CS3	36	34	30	36,700	X	X	X	X	X	X	X	X
Kec-CS4	20	17	16	5,400	X							
Tonalite of the Gray Bands (unit Kgb)												
Kgb-NT1	38	24	21	19,200	X	X	X	X			X	X
Kgb-NT2	24	16	18	6,900	X							X
Kgb-NT3	29	27	22	17,200	X	X	X					X

Table 3. Bulk rock sample number, dimensions, and type of tests performed.—Continued

Bulk sample number	Length (cm)	Width (cm)	Height (cm)	Approx. volume (cm³)	Type of test[1,2]							
					UCS	TRX	BTS		FT-CB		FT-CCNBD	
							//	⊥	//	⊥	//	⊥
Taft Granite (unit Kt)												
Kt-RA1	36	31	25	27,900	X	X	X	X	X		X	X
Kt-RA2	25	18	13	5,900			X				X	X
Kt-RA3	22	18	22	8,700	X				X			
Kt-RA4	24	15	17	6,100	X	X						
Diorite of North America (unit Kd)												
Kd-ZT1	35	30	26	27,300	X	X	X	X		X	X	X
Kd-ZT2	23	23	15	7,900			X				X	
Kd-ZT3	22	19	18	7,500	X	X						
Kd-ZT4	32	17	17	9,200	X							
Sentinel Granodiorite (unit Ks)												
Ks-IC1	41	25	26	26,700		X	X	X			X	X
Ks-IC2	35	21	21	15,400			X	X			X	X
Ks-IC3	36	22	17	13,500	X	X						
Ks-IC4	29	23	18	12,000	X							
Ks-IC5	27	19	14	7,200	X							
Half Dome Granodiorite (unit Khd)												
Khd-RW1	43	26	15	16,800	X							
Khd-RP1	27	22	27	16,000			X	X			X	X
Khd-RP2	33	30	23	22,800		X						
Khd-RP3	45	36	25	40,500								
Khd-RP4	40	34	19	25,800	X		X	X			X	X
Khd-ML1	36	33	30	35,600	X	X	X	X	3		X	X
Khd-ML2	45	37	32	53,300	X							
Khd-ML3	28	20	20	11,200								
Total number of tests					19	12	23		9		25	

[1]UCS, unconfined compression strength; TRX, triaxial compression test; BTS, Brazilian tensile test; FT–CB, mode I fracture toughness test by chevron bend method; FT–CCNBD, mode I fracture toughness test by cracked chevron notched Brazilian disk method.

[2]//, test performed on sample cored parallel to any existing fabric (for units Kgb and Ks); ⊥, test performed on sample cored perpendicular to any existing fabric and (or) perpendicular to the first coring direction.

2002) and this was readily apparent in our rock samples. Similarly, the tonalite of the Gray Bands (unit Kgb) shows consistent foliation on the rock face of El Capitan, dipping approximately 40° to the southwest (R. Putnam, written commun., 2014), although in our rock samples, it was hard to distinguish unequivocally. To investigate possible effects of anisotropy for these rock units, and also for potential influences in the other rock units investigated herein, we prepared oriented sample cores depending on the rock unit and rock strength test.

Rocks subject to unconfined compressive strength and triaxial compressive strength testing are typically loaded with their long axis oriented to the maximum principle stress (σ_1) direction. For tall, near-vertical cliffs, σ_1 is a vertical-oriented

Table 4. Approximate grain size of Yosemite Valley cliff rock units used in rock mechanics testing.

[mm, millimeters]

Geologic unit symbol	Rock unit	Bulk sample grain size[1]		Cylindrical sample grain size[2]	
		Average (mm)	Maximum (mm)	Average (mm)	Maximum (mm)
Kec	El Capitan Granite	8	20	6	9
Kgb	Tonalite of the Gray Bands	3	6	3	7
Kt	Taft Granite	2	6	3	6
Kd	Diorite of North America	1	5	1	3
Ks	Sentinel Granodiorite	4	10	4	8
Khd	Half Dome Granodiorite	5	10	4	8

[1]Measured from bulk samples collected in the field (see table 3). Cylindrical samples were cored from the bulk samples to ensure that no large (>9 mm) mineral grains were included in the cores.

[2]Measured from post-failure photographs of cylindrical samples used for unconfined compressive strength testing (see appendix 1).

stress representing rock overburden (figs. 3*A*, *B*). Thus, for these tests, we drilled and tested cores aligned with the field foliation direction if known (that is, for sample Kgb-NT2 and all unit Ks samples). For all other rock units, unconfined compressive strength and triaxial compressive strength tests were performed in a single direction on randomly oriented cores (since the field orientation of the rock blocks could not be determined).

Rocks subject to Brazilian tensile strength testing and fracture toughness testing are typically designed to fail in tension (fig. 3*C*), and, although failure surfaces might orient themselves across foliation, we were more interested in the minimum and maximum tensile and fracture strengths. Thus, for all rock units, we drilled cores and tested disk samples in two orthogonal directions. For rocks with identifiable existing foliation (sample Kgb-NT2 and all unit Ks samples), the coring directions for all Brazilian tensile strength and fracture toughness tests were oriented parallel and perpendicular to the foliation. For these tests on all other samples, we arbitrarily selected one direction for initial coring and drilled subsequent samples perpendicular to the first direction. In total, we prepared 34 cylindrical cores with a 55-mm diameter and 25 cylindrical cores with an 80-mm diameter.

We subsequently cut the 55-mm- and 80-mm-diameter cores using a saw to their respective lengths according to the standard size for each type of test (see subsequent Testing sections). We aimed for approximately 110- to 120-mm-long cylindrical samples for the unconfined and triaxial strength tests (approximate height to diameter ratio of 2:1), 80-mm-long samples for the Brazilian tensile strength tests (approximate length to diameter ratio of 1:1), 220-mm-long samples for the chevron bend (CB) fracture toughness tests (approximate length to diameter ratio of 4:1), and 30-mm-long samples for the cracked chevron notched Brazilian disk (CCNBD) fracture toughness tests (approximate diameter to thickness ratio of 2.7:1). Samples prepared for the fracture toughness tests required cutting a chevron-shaped notch into the core diameter. For the chevron bend fracture toughness samples, we cut the chevron notch into the side (long edge) and perpendicular to the core axis of the cylindrical sample according to test specifications (Franklin and others, 1988). For the cracked chevron notched Brazilian disk fracture toughness tests, we cut the chevron notch into each diametrical end of the disk sample (Fowell, 1995; fig. 6). After sample preparation, we measured and confirmed all sample dimensions to ensure that they remained within the valid geometrical range for each test specimen.

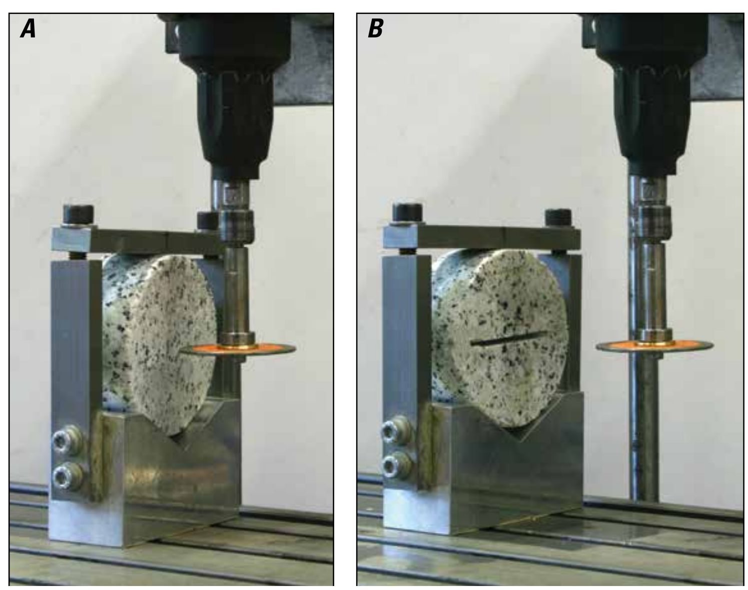


Figure 6. Photographs of rock sample preparation for cracked chevon notched Brazilian disk samples used for fracture toughness tests. Views before (*A*) and after (*B*) notch cutting. Intersecting chevron notches are cut into each end of the cylindrical disk.

Testing

To characterize the geomechanical strength properties of selected rocks from Yosemite Valley, we designed a testing campaign for the rock samples. For each rock unit, we performed the following tests (table 3):

- Three unconfined compressive strength tests (with a maximum of two tests conducted on a single bulk block sample),
- Two multistage triaxial compressive strength tests (conducted on different bulk block samples),
- Three Brazilian tensile strength tests (with at least two tests performed in perpendicular directions on the same bulk block sample), and
- Four cracked chevron notched Brazilian disk fracture toughness tests (with two sets of tests performed in perpendicular directions on two bulk block samples; exceptions were made for tonalite of the Gray Bands and diorite of North America (units Kgb and Kd) samples owing to a lack of sufficient core [see Results section]).

Because the cracked chevron notched Brazilian disk (CCNBD) fracture toughness test procedure had not yet been performed in the EPFL laboratory, we opted to test more standard (benchmark) chevon bend (CB) fracture toughness tests on four of the rock units (units Kec, Kt, Kd, and Khd) to investigate the quality of the results. These provided a check on the values obtained using the CCNBD method. Because no clear anisotropic effects were identified in the Brazilian tensile strength tests for these rocks, we did not perform the CB fracture toughness testing in orthogonal directions.

Unconfined Compressive Strength

We measured the unconfined compressive strength of each rock unit using the Swiss National Standard VSS–70353A (Swiss Association of Road and Transportation Experts, 2019a) (rock tests: resistance to uniaxial compression, modulus of deformation, and Poisson's ratio of cylindrical specimens). This test procedure is similar to ASTM D2938-95 (standard test method for unconfined compressive strength of intact rock core specimens; ASTM International, 1995). The test involves applying uniaxial (unconfined) compression on a cylindrical sample along the long axis (height) until failure and measuring the peak load and resulting sample deformation. Owing to the relative simplicity of this test, it is commonly used for initial rock strength characterization, but has also been used for more complex studies such as those aimed at quantifying brittle fracture (for example, Eberhardt and others, 1999).

Our cylindrical samples used for testing had a typical height (H) of 116 mm and typical diameter (D) of 54–56 mm (average $H/D = 2.14$). Prior to testing, we measured the mass of each sample and used the cylindrical dimensions to calculate their density. We performed all unconfined compression strength tests using a 2,000 kilonewton (kN) Walter + Bai AG load press (https://www.walterbai.com) and a self-controlled deformation rate of 0.1 percent per minute until failure. Our experimental setup is shown in figure 7.

During testing, we measured axial deformation of the samples using two linear variable differential transformer (LVDT) sensors (HBM W10TK type with ±10 mm range and <±0.4 percent accuracy) placed between the platens of the press, and measured radial deformation using an extensometer chain (Epsilon Technology model 3544–100M–250–ST with ±0.05 percent resolution) encircling the sample at its mid-height. We converted the maximum measured load, P (as measured by an HBM type 102–2000–DS Class 1, 2,000 kN load cell with 0.03 percent resolution), to unconfined compressive strength (σ_c) by dividing the load by the cylindrical cross section area ($A = \pi D^2/4$):

$$\sigma_c = \frac{P}{A} \tag{1}$$

In accordance with the testing procedure (Swiss National Standard VSS–70353A; Swiss Association of Road and Transportation Experts, 2019a), each sample was initially loaded to a value approximately 50 percent of the maximum expected compressive strength and then subsequently unloaded. The sample was then reloaded until failure; two loading curves are therefore apparent in the test results. Based on an initial test of sample RP4 (rock unit Khd), the value for the unloading-reloading cycles was set to be approximately 60 megapascals (MPa) of axial load for all subsequent tests. We calculated longitudinal (ε_1) and lateral (ε_3) strains through standard procedures from the axial and radial deformation data, and used these to calculate the modulus of elasticity (E_{50}; that is, at 50 percent peak strain as defined by the slope of the tangent line at this strain) and the Poisson's ratio (ν). In two tests (samples Ks-IC3 and Khd-RP4), the reloading curve was significantly different from the initial loading curve and we therefore calculated individual values of the modulus of elasticity for each load cycle of these two samples.

Triaxial Compressive Strength

We measured the triaxial compressive strength of each rock unit according to ASTM Standard D2664–86 (standard test method for triaxial compressive strength of undrained rock core specimens without pore pressure measurements; ASTM International, 1986). The test involves applying increasing axial load (stress) with constant radial compression on a cylindrical sample until failure and measuring the load and resulting sample deformation. The test has been used for a variety of investigations, including earthquake studies (for example, Lockner and Beeler, 2002) and for investigating the effects of cracking on fluid flow in rocks (for example, Zoback and Byerlee, 1975). We performed three-stage loading on each

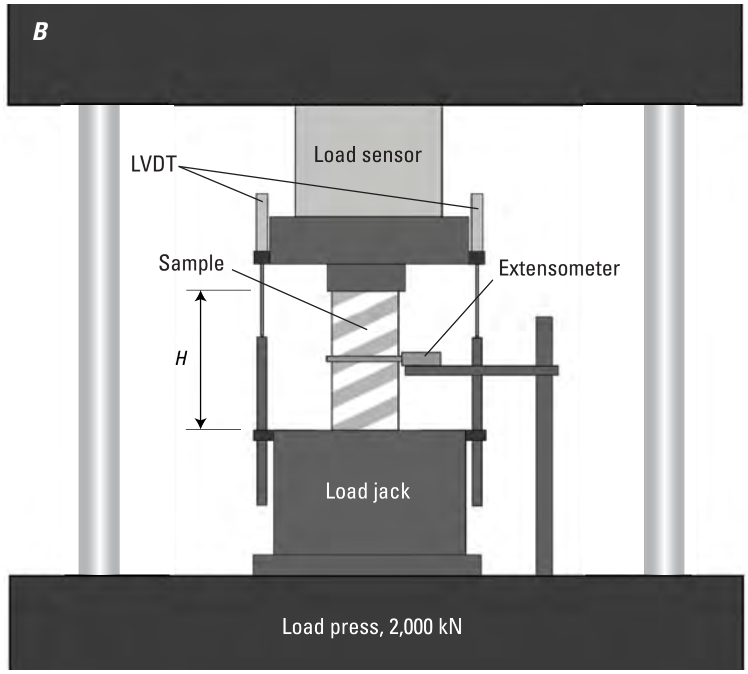


Figure 7. Image (*A*) and schematic diagram (*B*) showing unconfined compression strength rock testing laboratory setup at the École Polytechnique Fédérale de Lausanne (EPFL) rock mechanics laboratory in Lausanne, Switzerland. A rock sample (of height $H \approx 116$ millimeters) is placed axially between the platens (load jack and load sensor) and a servo-controller load jack compresses the sample in the axial direction, during which time the axial load, axial deformation, and radial deformation (extensometer; green sensor in *A*) are measured. LVDT, linear variable differential transformer; kN, kilonewtons.

sample to calculate the residual shear strength parameters on the Mohr-Coulomb failure envelope (see appendix 2); after reaching initial peak and residual conditions at the first load step, the confinement was either increased or decreased prior to the application of the next stage of axial loading until residual conditions were reached again.

Our cylindrical samples used in testing typically had a height (*H*) of 116 mm and diameter (*D*) of 54 mm (average $H/D = 2.16$). Prior to testing, we measured the mass of each sample and used the cylindrical dimensions to calculate their density. We performed all triaxial compressive strength tests using a 2,000 kN Walter + Bai AG load press (same as for the unconfined compressive strength tests), but here the test sample was enclosed in an impermeable but flexible membrane, and a triaxial compression cell (Hoek cell; see Hoek and Franklin, 1968) was used to apply radial confinement with pressurized oil. All tests were performed using a servo-controlled axial load, with the axial load increasing at a constant rate of 1 kN per second. Our experimental setup is shown in figure 8.

During testing, we measured axial load, confining pressure, and axial deformation. Axial load (*P*) was converted to axial stress (σ_1) by dividing by the sample cross-sectional area (*A*):

$$\sigma_1 = \frac{P}{A} \qquad (2)$$

Axial strain (ε_1) was determined by dividing the axial deformation by the original sample length.

Testing proceeded under constant confinement ($\sigma_{3\text{–}1}$) beginning either at 1 or 3 MPa until initial failure (that is, at peak stress conditions) defined by a peak in vertical stress ($\sigma_{1\text{–}1\text{peak}}$). A Mohr circle defining these (peak) conditions can be drawn considering the first confining pressure ($\sigma_{3\text{–}1}$) and the failure stress ($\sigma_{1\text{–}1\text{peak}}$). After the first signs of failure, we maintained the initial confining pressure until we reached subsequent stable sliding on the failure surface; this describes the residual conditions of the sample under the first step of confining pressure. Here, a Mohr circle can be drawn (see procedures and results in appendix 2) for the first residual conditions reached and is defined by the same confining pressure applied at the beginning of testing ($\sigma_{3\text{–}1}$) and a residual value of failure stress ($\sigma_{1\text{–}1\text{res}}$). After this we either increased or decreased the confining pressure by 1 MPa and continued axial loading until the sample showed signs of failure a second time. This defines a new residual Mohr circle, characterized by the new confining pressure ($\sigma_{3\text{–}2}$) and a new residual value of failure stress ($\sigma_{1\text{–}2\text{res}}$). We then repeated this procedure a third time to provide three stages in which to evaluate the residual Mohr-Coulomb shear strength parameters (residual cohesion, c_{res}, and residual friction angle, ϕ_{res}) for each sample. Once the entire test procedure was completed (all three loading stages), we recorded the failure angle (α) that formed within the sample with respect to the axial direction. Finally, we calculated the modulus of elasticity at 50 percent peak strain (E_{50}) for the first loading step before peak failure.

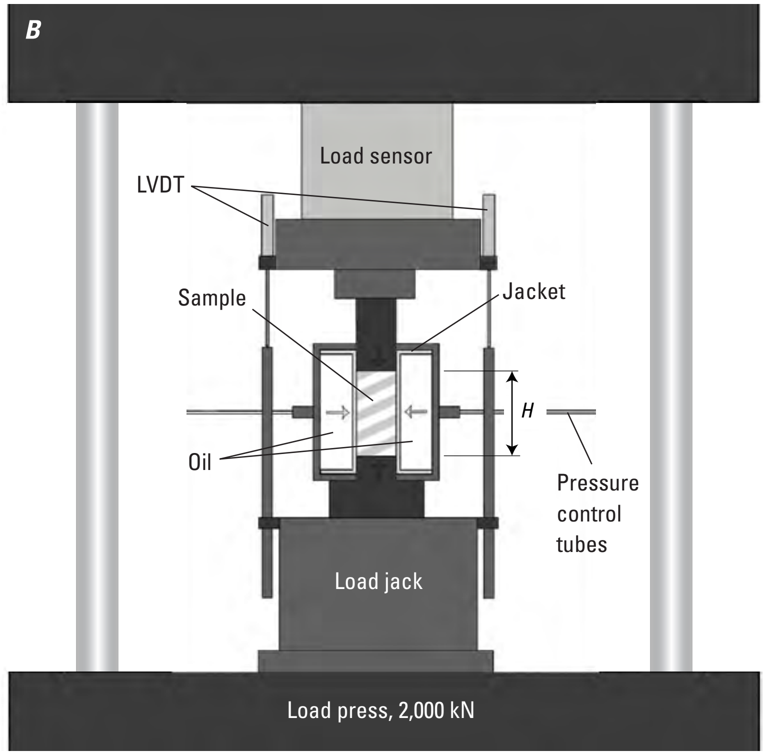


Figure 8. Image (*A*) and schematic diagram (*B*) showing triaxial compression strength rock testing laboratory setup at the École Polytechnique Fédérale de Lausanne (EPFL) rock mechanics laboratory in Lausanne, Switzerland. A rock sample (of height $H \approx 116$ millimeters) is placed in the Hoek cell (jacket filled with oil connected to confinement pressure through external tubes), which is subsequently placed axially between the platens (load jack and load sensor) at the top and bottom of the load press. A confinement pressure is applied to the outside of the sample using the Hoek cell and a servo-controller load jack compresses the sample, during which the axial load, axial deformation, and radial confinement are measured. After reaching peak failure during the first step of radial confinement, the confinement is increased or decreased between each stage prior to subsequent axial loading to obtain three points of failure along the Mohr-Coulomb residual strength envelope. LVDT, linear variable differential transformer; kN, kilonewtons.

For each rock unit, we performed a total of two tests for each sample type, one each in a staged increase and staged decrease format, to evaluate potential differences in residual values for the shear strength parameters from unloading versus loading stress paths. Testing two samples of the same rock unit also allowed us to obtain two values of peak failure conditions. These, along with the results of the unconfined compressive strength tests (at $\sigma_3 = 0$), provided three points in which to evaluate the peak Mohr-Coulomb shear strength parameters (peak cohesion, c_{peak}, and peak friction angle, ϕ_{peak})

Brazilian Tensile Strength

We measured the tensile strength of each rock unit using Swiss National Standard VSS–70354 (Swiss Association of Road and Transportation Experts, 2019b) (rock test: indirect tensile strength of cylindrical specimens—Brazilian test). This test procedure is similar to ASTM Standard D3967–16 (standard test method for splitting tensile strength of intact rock core specimens; ASTM International, 2016). The test involves applying diametrical compression on a cylindrical sample until tensile failure (splitting) occurs along the longitudinal axis of the sample. The peak load is measured during the test. The Brazilian test is considered an “indirect” method to measure the tensile strength of rock because it does not load the sample in tension directly (that is, by pulling on the sample from opposite ends). Direct tensile testing of rocks is possible (for example, ASTM International, 2008) and analyses have shown that the actual direct tensile strength of igneous rocks are about 80 percent of that obtained through Brazilian tensile strength testing (Perras and Diederichs, 2014), mainly owing to assumptions and limitations related to the Brazilian test (Li and Wong, 2013). However, because the direct tensile test is somewhat complicated to perform, the Brazilian test is widely used as a proxy for measuring the tensile strength of rock.

Our samples used for testing had a typical length (L) of 80 mm and typical diameter (D) of 80 mm (average $L/D = 1.00$). We performed all Brazilian tensile strength tests using a 2,000 kN Walter + Bai AG load press (same as for other tests), but here outfitted with two polyvinyl chloride (PVC) strips located between the end plates and the sample disc in order to reduce the high stress concentrations that would develop and otherwise cause premature cracking of the sample. Because of possible anisotropy affects, we performed at least one test in each of two diametrically opposed directions for each rock unit. The first test was performed with the sample fabric aligned parallel to the load; the second test was then performed with the sample oriented perpendicular to that in the first test (see also the Sample Preparation section for details on how the fabric was determined). Our experimental setup is shown in figure 9.

We converted the measured peak axial load (P) to a longitudinal tensile strength by assuming that an elastic state of uniform tensile stress (σ_t) occurs when the sample is loaded under a vertical compressive line load (that is, typical Brazilian disk testing assumptions):

$$\sigma_t = \frac{2P}{\pi LD} \tag{3}$$

where L and D are, respectively, the thickness and the diameter of the sample.

Mode I Fracture Toughness Strength

We measured the mode I (tensile) fracture toughness strength of each rock unit using the International Society of Rock Mechanics standards for fracture toughness. The fracture toughness of rocks has been investigated for a variety of reasons, including to understand fracturing of volcanic lava flows (for example, Balme and others, 2004) and the effect of temperature on rock blasting (for example, Dwivedi and others, 2000). We performed fracture toughness testing on two types of samples: chevron bend (CB) samples (Franklin and others, 1988) and cracked chevron notched Brazilian disk (CCNBD) samples (Fowell, 1995), however not all rock units were tested using both methods. CB samples are cylindrical in shape with a chevron notch cut perpendicular to the long axis of the cylinder (see inset in fig. 10*B*). The sample is supported at the cylinder end points and a vertical load is applied to the midpoint, with the chevron pointing downward. Alignment of the chevron notch and the axial load direction must be ensured prior to loading. During testing, the load and displacement of the chevron crack is measured until full fracture of the sample occurs. We performed three CB fracture toughness tests on the same boulder sample (Khd-ML1) at the beginning of the testing program to ensure proper calibration of the system and consistency of the results.

CCNBD samples are cylindrical disks (similar to Brazilian disk samples) with a chevron notch cut into both sides of the disk (see inset in fig. 10*D* and also the Sample Preparation section). The sample is positioned diametrically between two end platens and loaded until failure. The procedure is very similar to that for the Brazilian tensile strength tests and uses two PVC strips located between the end plates and the sample disc to reduce the high stress concentrations that would develop and otherwise cause premature cracking of the sample. Alignment of the chevron notch and the axial load direction must be ensured prior to loading. Two load-unload cycles are first performed at about 20 percent of the expected maximum load to ensure a perfect contact between the sample and load press. During testing, the load and displacement of the chevron notch are measured until full fracture of the sample occurs. If the crack opening is not deviating with respect to the axial direction of the notch, test results can be considered valid.

Our CB samples had a typical length (L) of 220 mm and typical diameter (D) of 56 mm (average L/D = 3.92). Prior to

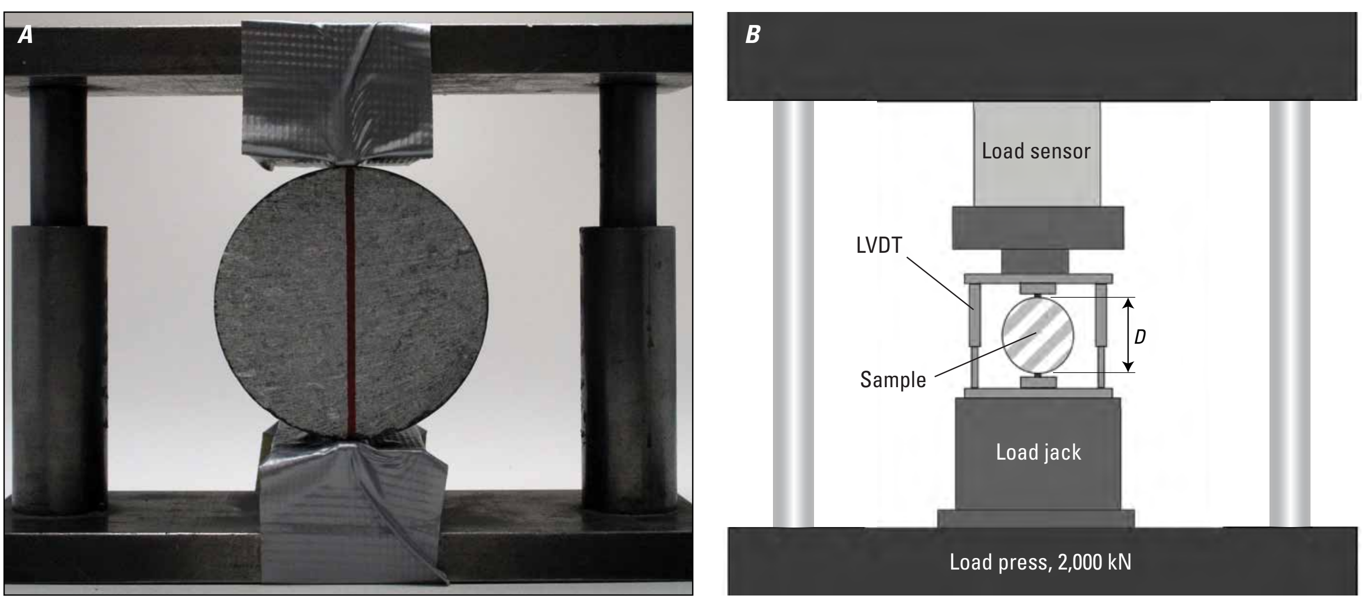


Figure 9. Image (*A*) and schematic diagram (*B*) showing Brazilian tensile strength rock testing laboratory setup at the École Polytechnique Fédérale de Lausanne (EPFL) rock mechanics laboratory in Lausanne, Switzerland. A rock sample (of diameter $D \approx 80$ millimeters) is placed diametrically between the platens at the top and bottom of the load press with a set of polyvinyl chloride (PVC) strips along each end to more uniformly distribute the axial load. Tensile splitting occurs along the length of the sample upon reaching peak axial load. LVDT, linear variable differential transformer; kN, kilonewtons.

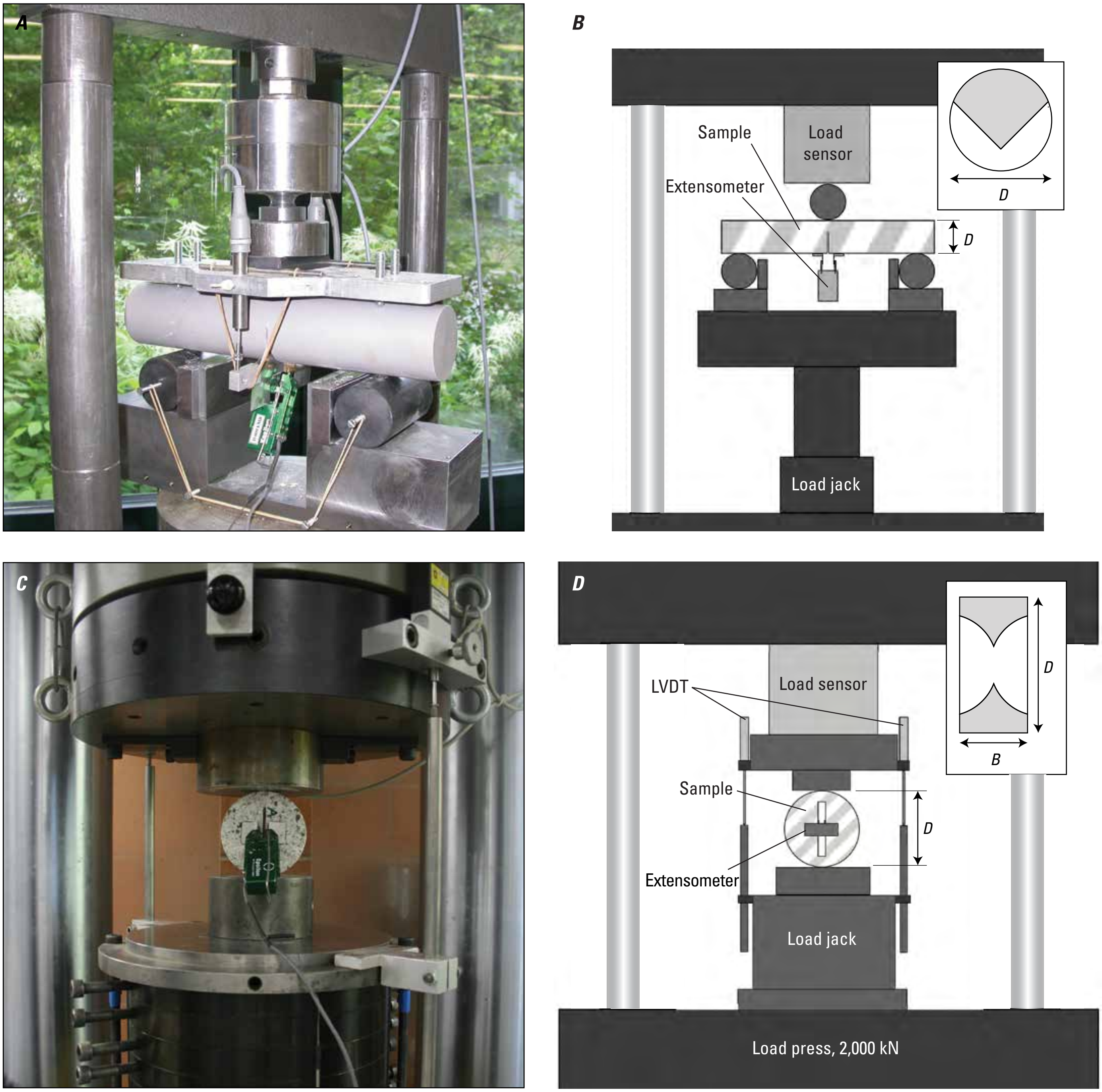


Figure 10. Mode I fracture toughness strength rock testing laboratory setup at the École Polytechnique Fédérale de Lausanne (EPFL) rock mechanics laboratory in Lausanne, Switzerland. Image (*A*) and schematic diagram (*B*) show the chevron bend (CB) test procedure. A cylindrical rock sample (of diameter $D \approx 56$ millimeters [mm]) with a chevron notch cut perpendicular to the long axis of the cylinder (see inset for cross section at the notch) is placed longitudinally and supported at the two ends with the chevron notch pointed downward. Upon loading from above, fracture occurs beginning at the chevron notch and failure ensues when the peak load is reached. Image (*C*) and schematic diagram (*D*) show the cracked chevron notched Brazilian disk (CCNBD) test procedure. A cylindrical disk ($D \approx 80$ mm and thickness $B = 30$ mm) with a chevron notch cut into the sides of the disk (see inset for cross section at the notch) is loaded diametrically. Upon loading from above, fracture occurs beginning at the chevron notch and failure ensues when the peak load is reached. LVDT, linear variable differential transformer; kN, kilonewtons.

testing, we measured the mass of each CB sample and used the cylindrical dimensions to calculate their density. Our CCNBD samples had a typical disk thickness (*B*) of 30 mm and typical *D* = 80 mm (that is, with radius *R* = 40 mm, resulting in average *B*/*R* = 0.75, meeting the criteria outlined by Fowell, 1995). We performed fracture toughness strength tests using a 10 kN Wykeham Farrance press (CB samples) and a 2,000 kN Walter + Bai AG load press (CCNBD samples), both with a self-controlled deformation rate of 0.003 mm per second until failure. During testing of the CB and CCNBD samples, the load point displacement (LPD; that is, the vertical displacement) is measured using two LVDT transducers placed on a gauge in direct contact with the rock next to the notch. The relative crack mouth opening displacement (CMOD) is measured using a sensor fixed on two reference marks glued to the core sample at the middle of the notch. Our experimental setup is shown in figure 10 for both CB and CCNBD type samples.

We calculated the mode I fracture toughness (K_{CB}, K_{IC}) using standard formulas for linear elastic fracture mechanics solutions of the CB (Franklin and others, 1988) and CCNBD (Fowell and Xu, 1993) geometries, respectively:

$$K_{CB} = \frac{F_{max}}{D^{1.5}} A_{min} \qquad \text{(CB tests)} \qquad (4a)$$

$$K_{IC} = \frac{P_{max}}{B\sqrt{R}} Y^{*}_{min} \qquad \text{(CCNBD tests)} \qquad (4b)$$

where

F_{max} is the peak vertical load,
A_{min} is a dimensionless factor,
D is the diameter,
B is the disk thickness,
R is the radius,
P_{max} is the peak vertical load, and
Y^{*}_{min} is the critical dimensionless stress intensity factor value that is based on sample measurements used to compute geometrical parameters as defined in the test procedures (Fowell and Xu, 1993).

The dimensionless factor, A_{min}, is defined as

$$A_{min} = \left[1.835 + 7.15a_0 / D + 9.85\left(a_0 / D\right)^2\right] \times S / D \qquad (5)$$

where

S is the distance between the support points (equal to 3.33*D*) and
a_0 is the chevron tip distance from the specimen surface (equal to 0.15*D*).

Results

We present our test results as a series of tables and bar charts to provide both the individual testing values for each rock sample and to also provide a visual summary comparison of average values for each rock mechanics strength parameter. In the bar charts, we chose the color for each rock unit to coincide with the geologic map in figure 4 (slightly modified from Peck, 2002, and Putnam and others, 2015).

Unconfined Compressive Strength

The unconfined compressive strength of the six granitic rock units from Yosemite Valley (table 5, fig. 11) ranges from 79 (unit Ks) to 190 MPa (unit Kd), with average values ranging from 118 (unit Ks) to 149 MPa (units Kt and Kd). The modulus of elasticity (from unconfined compressive strength testing) of the rock units (fig. 12) ranges from 24.8 (unit Khd, average value for RP4) to 52.6 gigapascals (GPa) (unit Kd), with average values ranging from 31.6 (unit Kec) to 40.2 GPa (unit Kd). The Poisson's ratio (from unconfined compressive strength testing) of the rock units (fig. 13) ranges from 0.06 (unit Kd) to 0.40 (unit Ks), with average values ranging from 0.11 (unit Kd) to 0.23 (unit Kt). Overall, the test results highlight the stiff, yet brittle, behavior of granitic rocks with steep loading curves and rapid strength loss following peak strength. Results for all unconfined compressive strength tests are provided in table 5. Additional test results (stress-strain curves) and before and after testing photographs for each sample are provided in appendix 1.

The two rock units with the highest average unconfined compressive strength (units Kt and Kd) are also the units with the smallest individual mineral grain size (table 4). The lowest average strength is for unit Ks, which exhibits the highest degree of fabric of all the tested rocks. The results for some rock units (units Kgb and Kt) are fairly homogenous (fig. 11), potentially indicating homogeneity of these rock blocks; other units (for example, units Kec and Kd) exhibited more pronounced differences between maximum and minimum values of the unconfined compressive strength. The modulus of elasticity and Poisson's ratio are lowest and highest, respectively, for the two samples (Ks-IC3 and Khd-RP4) whose reloading stress-strain curve was significantly different than the initial load curve (table 5, also see appendix 1). This was likely due to the initial load path for these two tests being carried to greater than 80 percent of their peak compressive strength. In other tests, the reload curve was initiated at less than 50 percent of peak strength. As these tests were performed early in the testing program, their range of expected peak compressive strengths were still unknown. Thus, these two samples show a more plastic response; however, they are also the samples with the lowest overall unconfined compressive strength (fig. 11). Reported values of the modulus of elasticity for samples KS-IC3 and Khd-RP4 are the average of the initial load and reload curves. The strength and elastic parameter values for these samples are not included in the average values reported for these rock units (figs. 11–13).

Table 5. Unconfined compression strength test results for six Yosemite Valley rock units.

[*H*, cylindrical sample height; *D*, cylindrical sample diameter; σ_c, unconfined compressive strength; E_{50}, elastic modulus at 50 percent strain; *v*, Poisson's ratio; mm, millimeter; t/m^3, metric tons per cubic meter; MPa, megapascals; GPa, gigapascals]

Sample number	H (mm)	*D* (mm)	Density (t/m^3)	σ_c (MPa)[1]	E_{50} (GPa) (1st cycle)	E_{50} (GPa) (2nd cycle)[1]	*v*
El Capitan Granite (unit Kec)							
Kec-CS1	109.2	56.0	2.64	129.6	31.1	-	0.22
Kec-CS3	116.4	55.7	2.70	110.5	26.7	-	0.20
Kec-CS4	116.5	54.1	2.62	170.7	37.1	-	0.25
Tonalite of the Gray Bands (unit Kgb)							
Kgb-NT1	117.1	54.3	2.78	120.2	34.1	-	0.18
Kgb-NT2	118.8	54.3	2.74	133.6	35.9	-	0.22
Kgb-NT3	117.4	54.4	2.73	136.6	38.9	-	0.22
Taft Granite (unit Kt)							
Kt-RA1	116.4	54.2	2.62	159.7	34.3	-	0.23
Kt-RA3	115.9	54.0	2.63	136.0	31.1	-	0.27
Kt-RA4	115.9	54.4	2.59	150.1	32.6	-	0.20
Diorite of North America (unit Kd)							
Kd-ZT1	116.8	54.4	2.81	141.9	35.6	-	0.06
Kd-ZT3	116.7	54.3	2.80	115.6	32.4	-	0.11
Kd-ZT4	115.8	54.4	2.88	190.0	52.6	-	0.16
Sentinel Granodiorite (unit Ks)							
Ks-IC3	118.8	54.4	2.77	78.7	21.3	30.8	0.40
Ks-IC4	119.3	54.4	2.79	117.2	44.4	-	0.19
Ks-IC5	119.4	54.4	2.78	119.0	35.3	-	0.24
Half Dome Granodiorite (unit Khd)							
Khd-RW1	117.5	54.3	2.73	129.5	37.3	-	0.23
Khd-RP4	116.0	54.3	2.65	92.1	22.2	27.4	0.39
Khd-ML1	111.0	54.3	2.66	113.6	32.4	-	0.16
Khd-ML2	116.5	54.3	2.67	129.7	36.8	-	0.21

[1]Two moduli are provided for samples Ks-IC3 and Khd-RP4 because their reload stress-strain curves were significantly different compared to their initial load curves. Values plotted in figure 12 are the average of the two values for each rock sample.

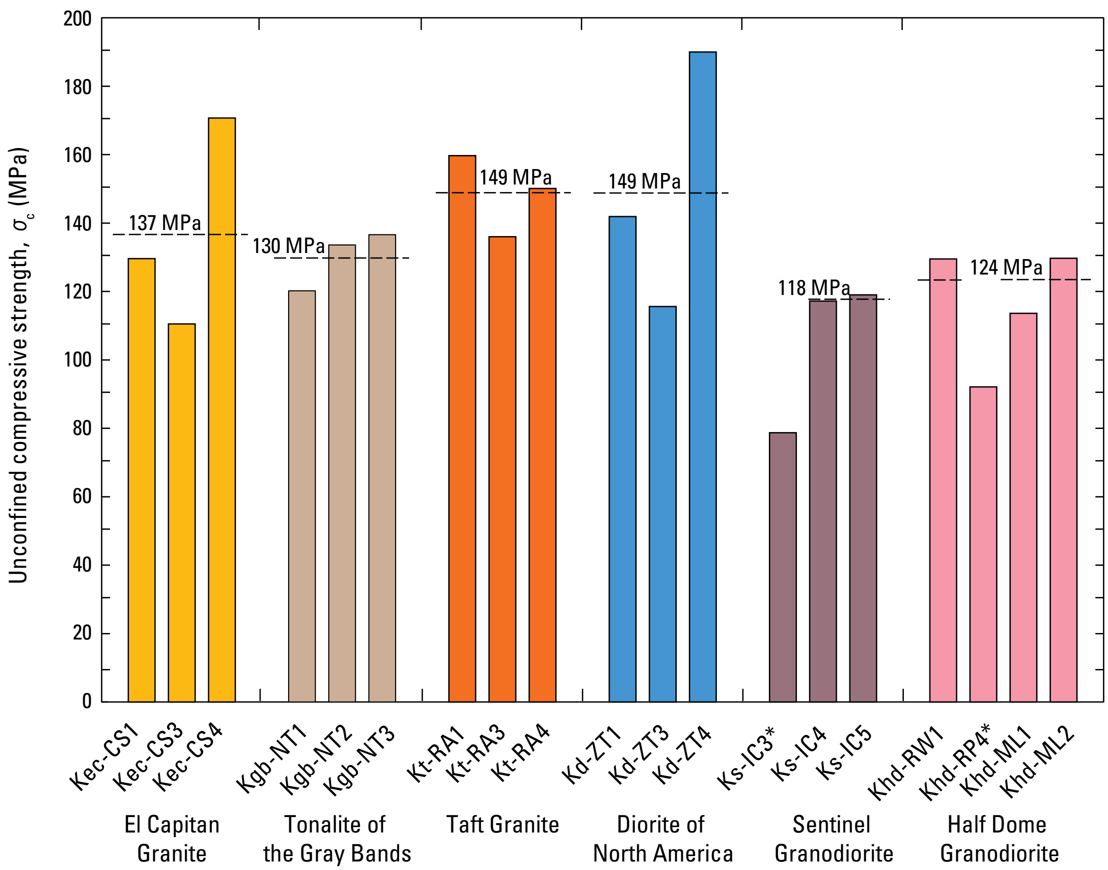


Figure 11. Plot of unconfined compression strength test results (in megapascals [MPa]) for six Yosemite Valley rock units. Average values for each unit are indicated by dashed horizontal black lines. Average values for the Sentinel Granodiorite (unit Ks) and Half Dome Granodiorite (unit Khd) do not include results from samples Ks-IC3 and Khd-RP4 (denoted by asterisks), respectively.

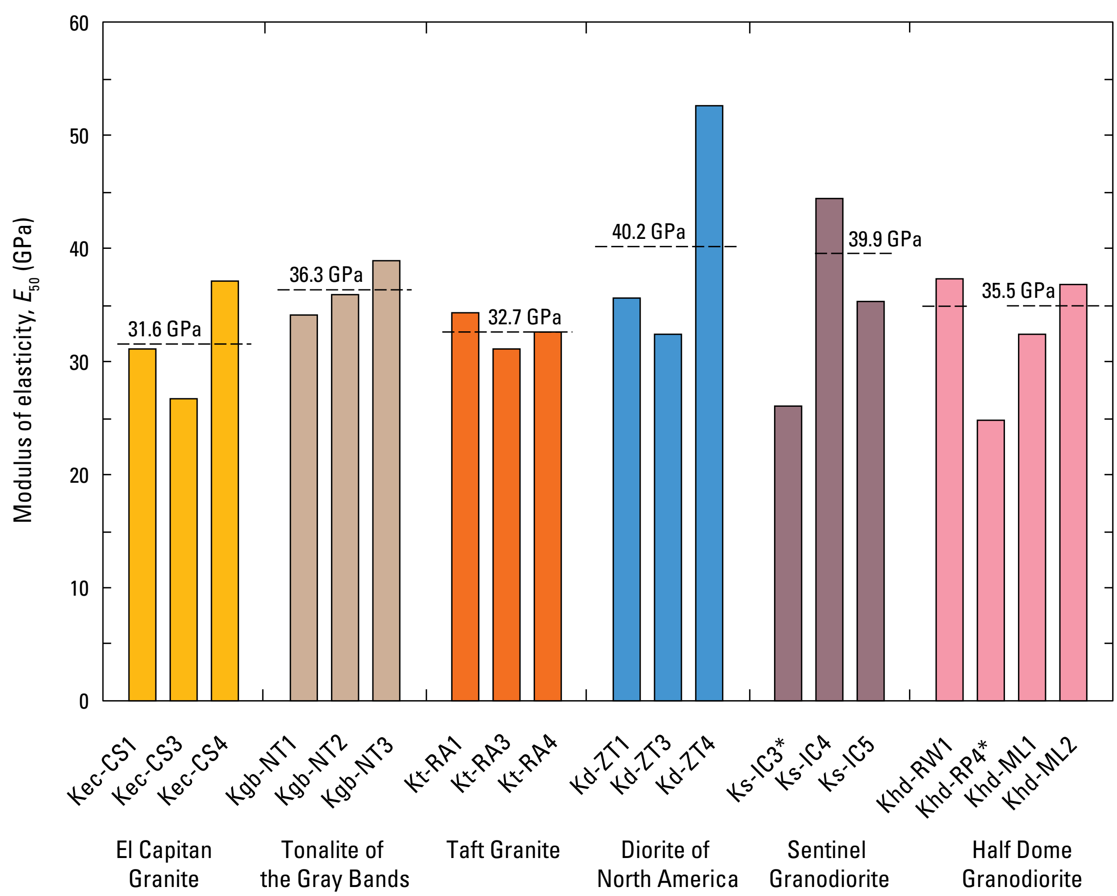


Figure 12. Plot of unconfined compression elastic modulus test results (in gigapascals [GPa]) for six Yosemite Valley rock units. Average values for each unit are indicated by dashed horizontal black lines. Average values for the Sentinel Granodiorite (unit Ks) and Half Dome Granodiorite (unit Khd) do not include results from samples Ks-IC3 and Khd-RP4 (denoted by asterisks), respectively.

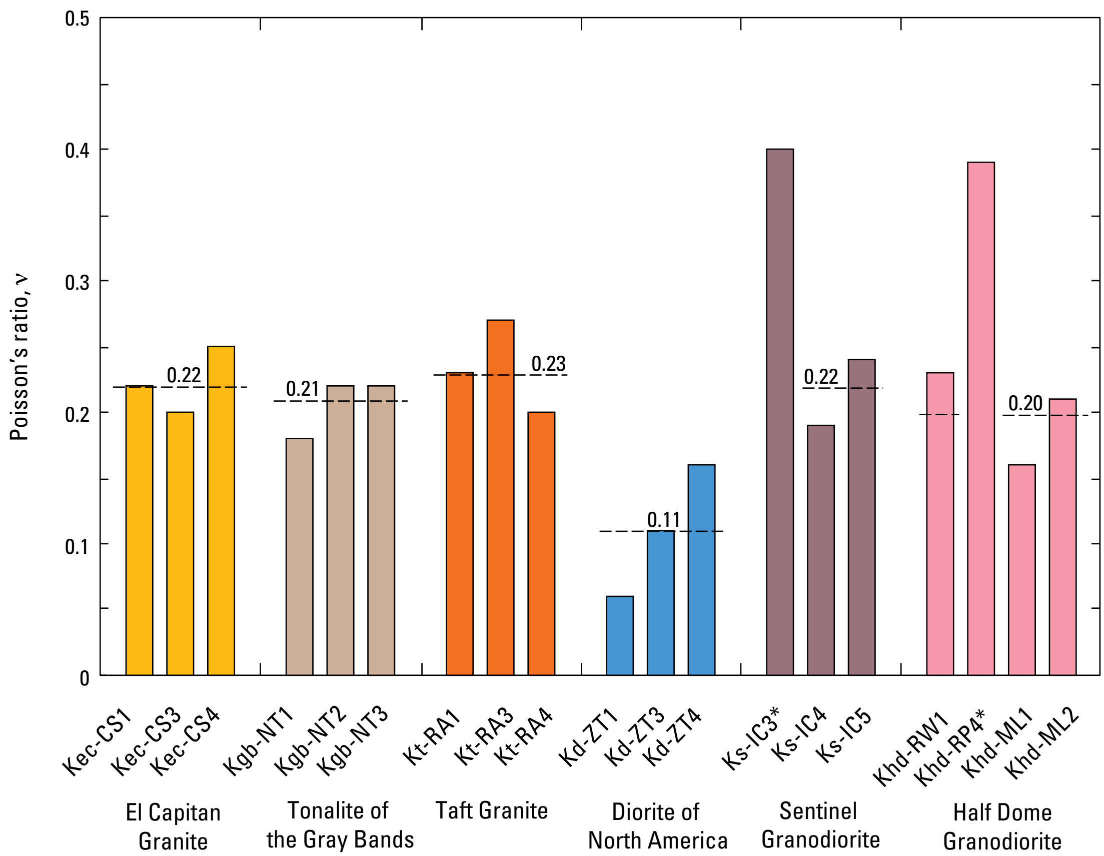


Figure 13. Plot of unconfined compression Poisson's ratio test results for six Yosemite Valley rock units. Average values for each unit are indicated by dashed horizontal black lines. Average values for the Sentinel Granodiorite (unit Ks) and Half Dome Granodiorite (unit Khd) do not include results from samples Ks-IC3 and Khd-RP4 (denoted by asterisks), respectively.

Triaxial Compressive Strength

We calculated both residual and peak Mohr-Coulomb shear strength parameters for six rock units from Yosemite Valley (table 6) from the triaxial compressive strength data. We fit linear regressions to the data over a span of confinement from 0 to 3 MPa. Residual strength parameters are based on the results from the multistage triaxial testing on each sample. Peak strength parameters are based on the results from the first stage of triaxial testing on samples from the same rock unit and location, combined with the results from unconfined compressive strength testing from these same samples (rock blocks). For determination of peak strength parameters, we evaluated the data by fitting the Mohr-Coulomb strength envelope in both σ_3 versus σ_1 stress space (best fit linear regression) and by drawing the best fit tangential line to the peak Mohr's circles in normal versus shear stress space. We present both sets of results in tables and charts, but because the results are quite consistent, we only discuss the average of these results in the subsequent discussion.

The Mohr-Coulomb residual shear strength parameters (friction angle, ϕ_{res}, and cohesion, c_{res}) span a fairly narrow range, with average ϕ_{res} values varying from 48° (unit Ks) to 53° (unit Kt) (fig. 14*A*) and average c_{res} values varying from 1.3 (unit Kgb) to 2.9 MPa (unit Khd) (fig. 15*A*). Peak shear strength parameters (ϕ_{peak} and c_{peak}) span a wider range, with average ϕ_{peak} values varying from 51° (unit Kd) to 75° (unit Khd) (fig. 14*B*) and average c_{peak} values varying from 6.6 (unit Khd) to 25.6 MPa (unit Kd) (fig. 15*B*). The peak results from unit Khd are not directly comparable to the other rock units because of the smaller range in which they are calculated. For unit Khd, no tests were performed at the higher confinement level (that is, σ_3 = 3 MPa); the peak failure envelope for unit Khd is therefore steeper and with lower intercept (ϕ_{peak} = 75° and c_{peak} = 6.6 MPa) compared to other units (ϕ_{peak} between 51 and 62° and c_{peak} between 12.5 and 25.6 MPa). The overall

Table 6. Triaxial compression residual strength test results for six Yosemite Valley rock units.

[*H*, cylindrical sample height; *D*, cylindrical sample diameter; α, failure plane angle with respect to the cylindrical long axis; σ_3, confinement stress (3 point with first listed point coincident with σ_{1p}); σ_{1p}, peak normal stress; ϕ_{res}, residual friction angle; c_{res}, residual cohesion; E_{50}, elastic modulus at 50 percent strain; mm, millimeter; t/m³, metric tons per cubic meter; MPa, megapascals; GPa, gigapascals]

Sample number	*H* (mm)	*D* (mm)	Density (t/m³)	α (degrees)	σ_3 (MPa)	σ_{1p} (MPa)	ϕ_{res} (degrees)	c_{res} (MPa)	E_{50} (GPa)
El Capitan Granite (unit Kec)									
Kec-CS1	117.3	54.3	2.67	26	1, 2, 3	154.4	48	2.5	30.8
Kec-CS3	116.4	54.3	2.69	26	3, 2, 1	157.3	56	0.3	24.6
Tonalite of the Gray Bands (unit Kgb)									
Kgb-NT1	117.2	54.4	2.77	26	1, 2, 3	132.9	51	1.7	25.5
Kgb-NT3	117.5	54.4	2.72	26	3, 2, 1	166.7	53	0.9	29.5
Taft Granite (unit Kt)									
Kt-RA1	116.4	54.4	2.60	26	1, 2, 3	179.4	51	2.8	26.5
Kt-RA4	115.8	54.4	2.60	26	3, 2, 1	200.8	55	0.6	24.4
Diorite of North America (unit Kd)									
Kd-ZT1	116.8	54.3	2.80	26	1, 2, 3	153.1	48	2.4	26.7
Kd-ZT3	116.8	54.4	2.80	26	3, 2, 1	166.0	50	0.6	29.5
Sentinel Granodiorite (unit Ks)									
Ks-IC1	119.3	54.3	2.77	26	1, 2, 3	111.1	45	2.4	24.7
Ks-IC3	119.0	54.4	2.76	26	3, 2, 1	115.1	51	0.6	20.0
Half Dome Granodiorite (unit Khd)									
Khd-RP2	116.5	54.2	2.64	26	1, 2, 3	202.7	52	2.4	31.6
Khd-ML1	116.5	54.2	2.66	26	1, 2, 3	150.4	46	3.4	32.0

behavior of the samples in triaxial compression indicate a brittle failure mechanism with a steep shear surface crossing plane (approximately 26° as measured from the long axis of the cylindrical samples in all triaxial tests; table 6, see also photographs in appendix 2).

The rock units with the highest overall shear strength (at the confinement conditions under which testing occurred) are units Khd and Kt at residual conditions, and units Kd and Kt at peak conditions (fig. 16). The peak results are a consequence of the high cohesion of units Kd and Kt (fig. 15*B*) obtained via the use of the unconfined compressive strength results (fig. 11), which were also high for these rock units. We note again that the peak shear strength results for unit Khd cannot be compared directly because of the different (lower) confinement conditions under which this rock unit was tested.

The results from the multistage testing indicate that tests performed using stepped increases in confinement result in significantly higher residual shear strength envelopes compared to testing performed with stepped decreases in confinement (fig. 16*A*). These results are in agreement with others (for example, Taheri and Chandra, 2013) who suggested that this behavior may be due to the extreme brittle behavior (non-strain-hardening) of the samples by the time they reach the lowest confinement stress.

The average modulus of elasticity of the rock units varies between 22.4 (unit Ks) and 31.8 GPa (unit Khd) (fig. 17). As expected, these values are all lower than those obtained from unconfined compressive testing and highlight the slightly more ductile response obtained as a result of confinement. Results for all triaxial compressive strength tests are provided in table 6 for residual strength values and table 7 for peak strength values. Additional test results (stress-strain curves and Mohr-Coulomb strength envelopes) and before and after testing photographs for each sample are provided in appendix 2.

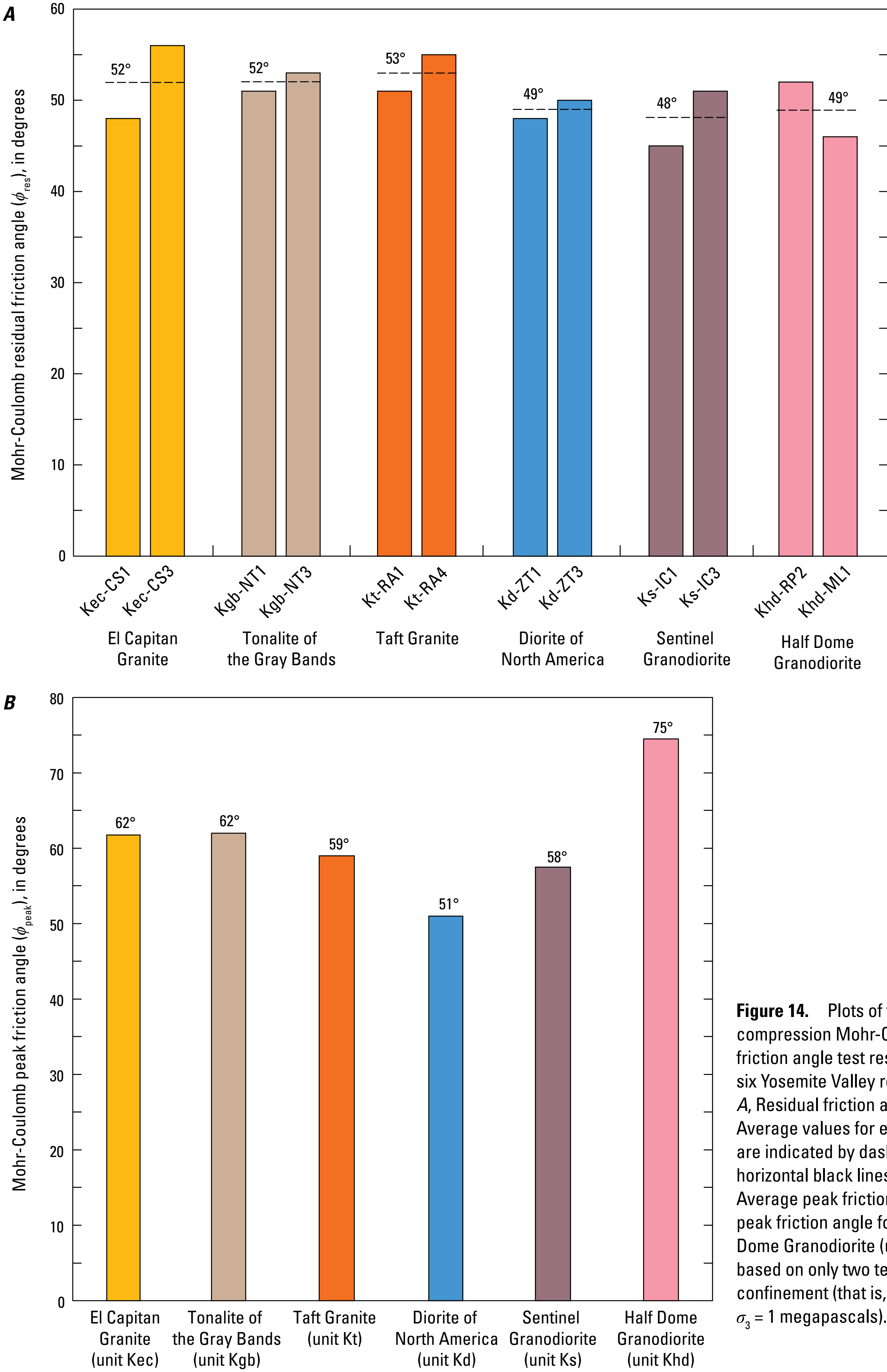
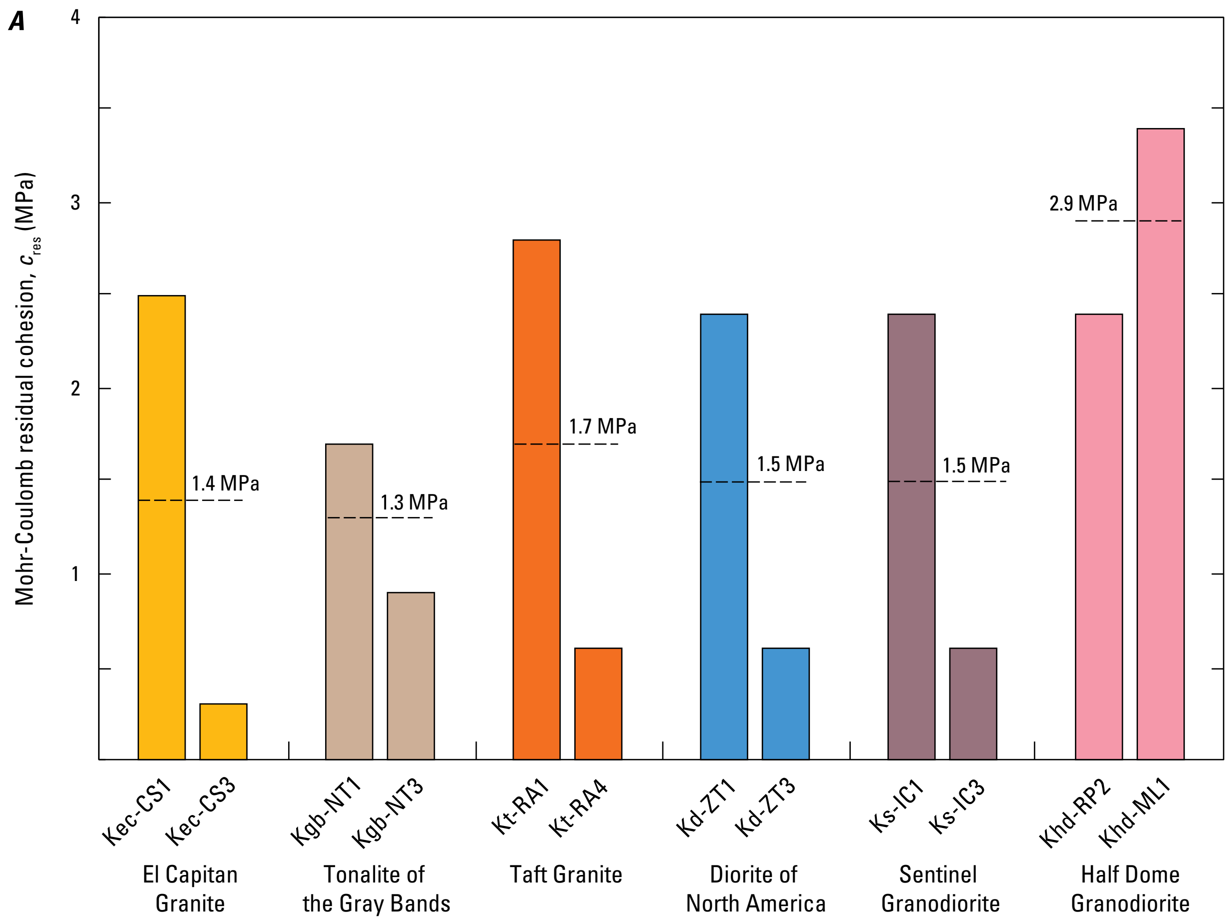


Figure 14. Plots of triaxial compression Mohr-Coulomb friction angle test results for six Yosemite Valley rock units. *A*, Residual friction angle. Average values for each unit are indicated by dashed horizontal black lines. *B*, Average peak friction angle. The peak friction angle for the Half Dome Granodiorite (unit Khd) is based on only two tests at low confinement (that is, $\sigma_3 = 0$ and $\sigma_3 = 1$ megapascals).



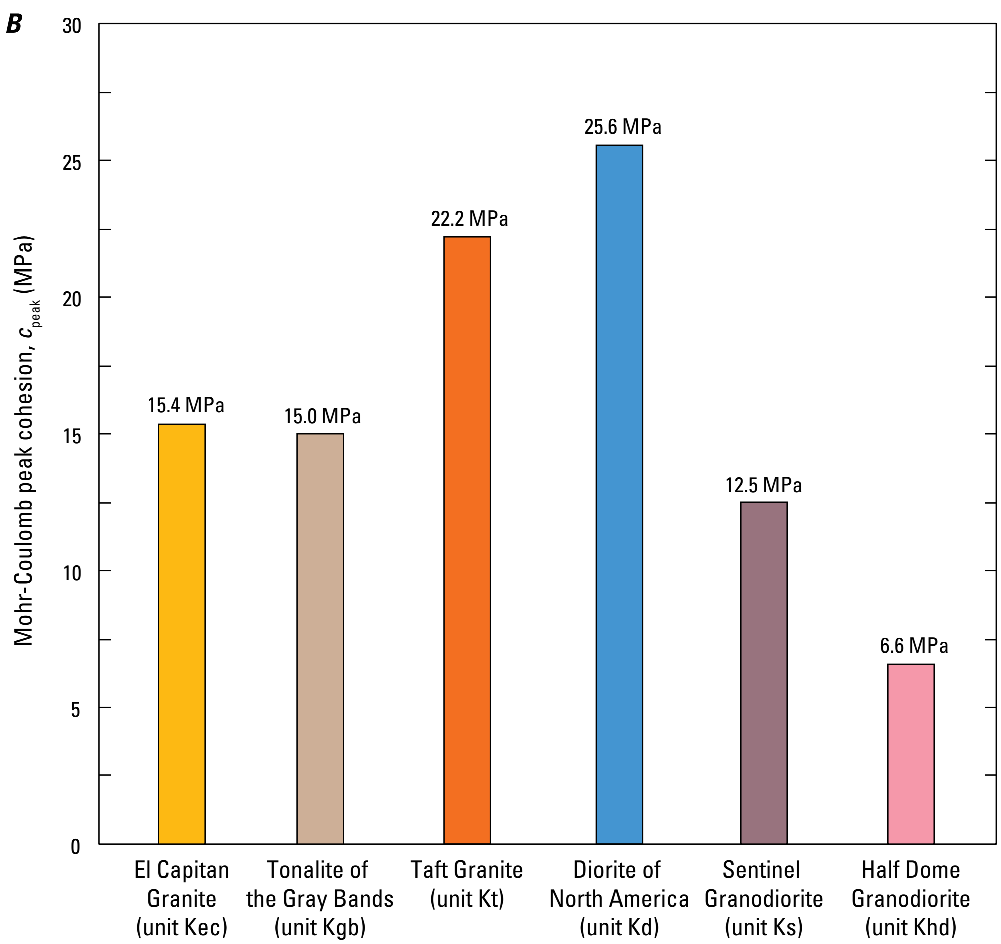


Figure 15. Plots of triaxial compression Mohr-Coulomb cohesion test results (in megapascals [MPa]) for six Yosemite Valley rock units. *A*, Residual cohesion. Average values for each unit are indicated by dashed horizontal black lines. *B*, Average peak cohesion. The peak cohesion for the Half Dome Granodiorite (unit Khd) is based on only two tests at low confinement (that is, $\sigma_3 = 0$ and $\sigma_3 = 1$ MPa).

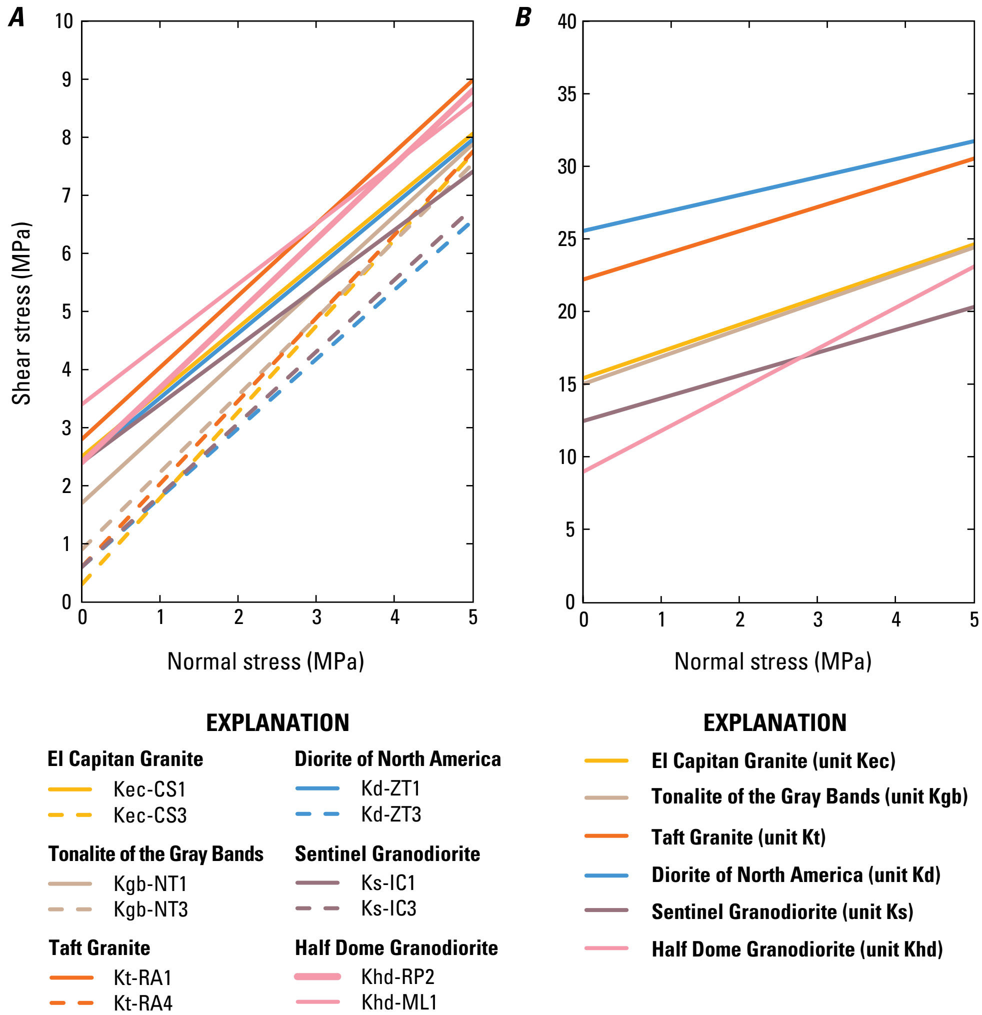


Figure 16. Plots of Mohr-Coulomb shear strength failure envelopes (in megapascals [MPa]) based on triaxial compression and unconfined compression testing (for peak values) for six Yosemite Valley rock units. *A*, Residual Mohr-Coulomb failure envelopes based on data from table 6. Stage-increase tests are represented by solid lines, stage-decrease tests are represented by dashed lines. *B*, Peak Mohr-Coulomb failure envelopes based on average data from table 7. The peak strength parameters for the Half Dome Granodiorite (unit Khd) are based on only two tests at low confinement (that is, $\sigma_3 = 0$ and $\sigma_3 = 1$ MPa).

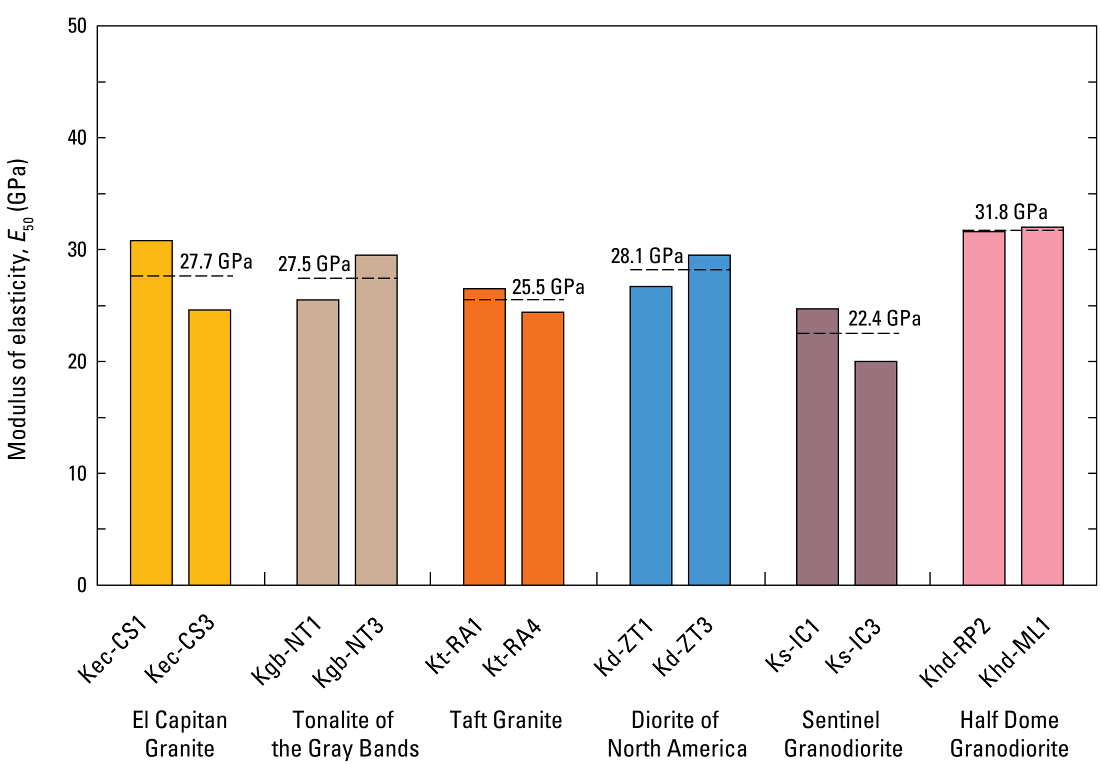


Figure 17. Plot of triaxial compression elastic modulus test results (in gigapascals [GPa]) for six Yosemite Valley rock units. Average values for each unit are indicated by dashed horizontal black lines.

Table 7. Triaxial compression peak strength test results for six Yosemite Valley rock units.

[σ_c, unconfined compressive strength (see table 5); σ_3, confinement stress coincident with σ_{1p}; σ_{1p}, peak normal stress; ϕ_{peak}, peak friction angle; c_{peak}, peak cohesion; MPa, megapascals]

Sample number	σ_c[3] (MPa)	σ_3[3] (MPa)	σ_{1p} (MPa)	ϕ_{peak}[1] (degrees)	c_{peak}[1] (MPa)	ϕ_{peak}[2] (degrees)	c_{peak}[2] (MPa)
El Capitan Granite (unit Kec)							
Kec-CS1	[129.6]	1	154.4	60	16.6	63	14.1
Kec-CS3	110.5	3	157.3				
Tonalite of the Gray Bands (unit Kgb)							
Kgb-NT1	120.2	1	132.9	62	15.0	62	15.0
Kgb-NT3	[136.6]	3	166.7				
Taft Granite (unit Kt)							
Kt-RA1	159.7	1	179.4	59	22.3	59	22.1
Kt-RA4	[150.1]	3	200.8				
Diorite of North America (unit Kd)							
Kd-ZT1	141.9	1	153.1	51	25.6	51	25.5
Kd-ZT3	[115.6]	3	166.0				
Sentinel Granodiorite (unit Ks)							
Ks-IC1	-	1	111.1	56	13.4	59	11.6
Ks-IC3	78.7	3	115.1				
Half Dome Granodiorite (unit Khd)[4]							
Khd-RP2	92.1	1	202.7	79	4.4	78	4.0
Khd-ML1	113.6	1	150.4	71	9.4	70	8.5

[1]Parameter based on the slope of the linear regression in σ_1-σ_3 plotting space (see appendix 2).

[2]Parameter based on the best-fit tangent to the Mohr circles in normal stress-shear stress plotting space (see appendix 2).

[3]Peak Mohr-Coulomb strength parameters were determined using one unconfined compression and two triaxial tests data points. Values in brackets were not used. Only small variations in strength parameters result from using the values in brackets.

[4]Peak Mohr-Coulomb strength parameters for samples Khd-RP2 and Khd-ML1 represent low confining stresses (0 to 1 MPa) and are therefore not comparable to results from other rock units with samples tested at higher confinement (0 to 3 MPa). Peak strength parameters for sample Khd-RP2 were evaluated using the unconfined compressive strength from sample Khd-RP4 (see table 5).

Brazilian Tensile Strength

The Brazilian tensile strength (σ_t) of the six granitic rock units from Yosemite Valley (table 8, fig. 18) ranges from 3.5 (unit Khd) to 9.4 MPa (unit Kgb) with average values ranging from 4.8 (unit Khd) to 8.2 MPa (unit Kgb). Overall, the test results highlight the weak behavior of granitic rocks in tension; values of tensile strength are on the order of 4 to 6 percent of the unconfined compressive strength. Notably, the rock unit with the highest average tensile strength (unit Kgb) does not have the highest compressive strength, thus indicating important differences in rock mechanics behavior with rock type. Results for all Brazilian tensile strength tests are provided in table 8. No photographs were taken before and after samples were tested and stress-strain curves were not recorded.

There is little variation with the average values of tensile strength across the samples, with the exception of the Half Dome Granodiorite (unit Khd). Most individual tensile tests of all rock units resulted in values between 6 and 9 MPa. However, for the Half Dome Granodiorite, four tests on two samples (Khd-RP1 and Khd-RP4) resulted in much lower values (average of 3.9 MPa) than even other samples (Khd-ML1; average of 6.7 MPa) of the same unit. These could indicate some expected variation of strength values from one location to another (that is, between Royal Prerogative Flake and Mirror Lake; fig. 4). However, the average of all tests on the Half Dome Granodiorite is still lower than all other rock units and is consistent with the Half Dome Granodiorite also having low average unconfined compression strength compared to most other rock units.

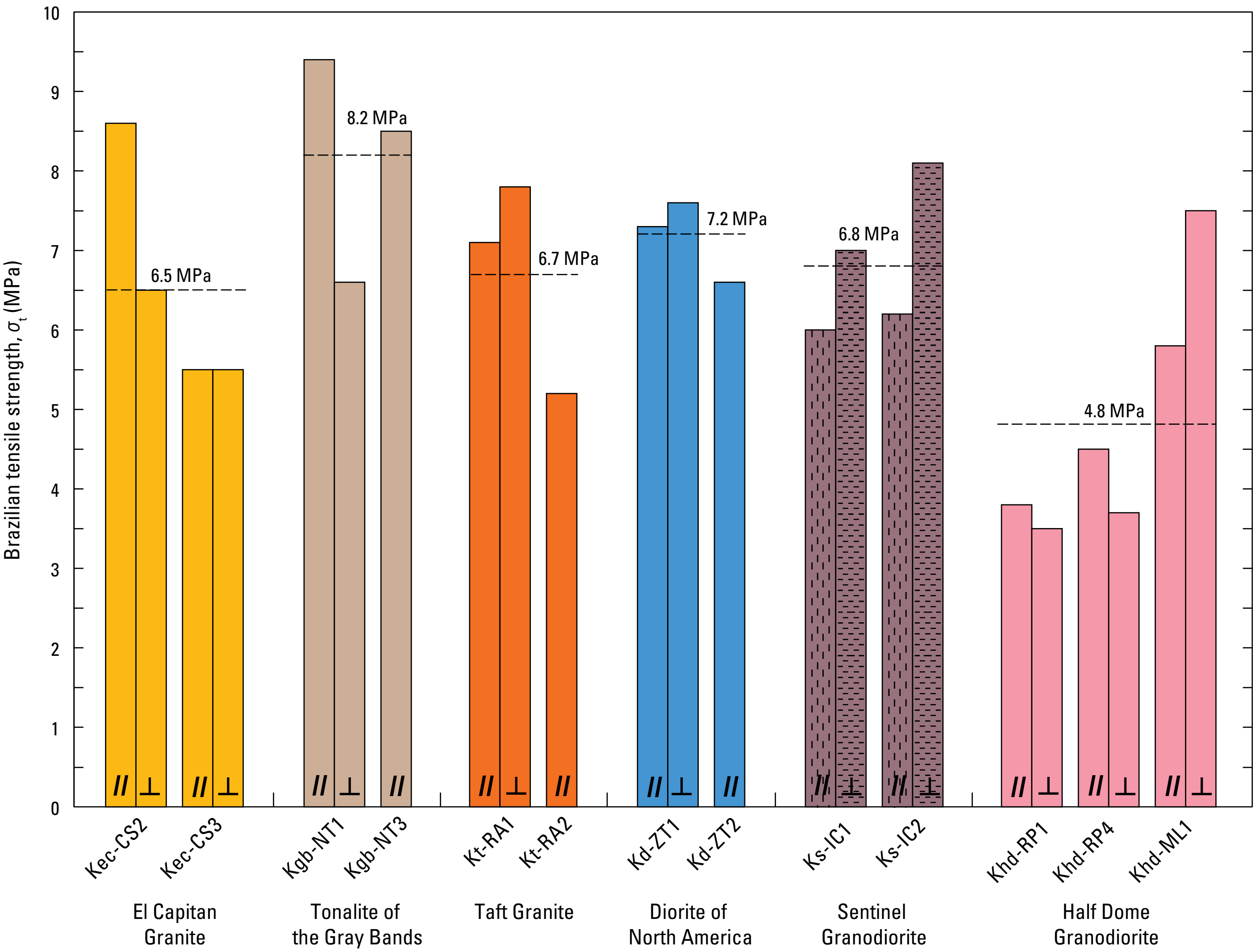


Figure 18. Plot of Brazilian tensile strength test results (in megapascals [MPa]) for six Yosemite Valley rock units. Average values for each unit are indicated by dashed horizontal black lines. For Sentinel Granodiorite (unit Ks) samples, patterns show the rock fabric. //, parallel; ⊥, perpendicular.

The Brazilian tensile strength testing was performed on disk samples cored in two orthogonal directions for each rock sample to assess for possible influences of fabric layering (for units Kgb and Ks) or indications of anisotropy (for all other rock units). Although many rock samples (for example, Kec-CS3, Kt-RA1, Kd-ZT1, Khd-RP1, and Khd-RP4) showed little variation (σ_t difference less than 1.0 MPa) with perpendicularly oriented sample testing, the results suggest at least some possible anisotropic effects for some rock units. The unit with the most visible fabric (unit Ks) had an average difference of 1.5 MPa between perpendicularly oriented samples; tensile strength was weaker when loaded parallel to visible fabric. For the tonalite of the Gray Bands (unit Kgb), the paired-orthogonal testing was performed only on a block sample without visible fabric (Kgb-NT1). However, the results indicate an anisotropic response with a difference of 2.8 MPa between perpendicularly oriented samples. Two other rock samples without visible or known fabric (Kec-CS2 and Khd-ML1) also showed an apparent anisotropic response (that is, differences of 2.1 and 1.7 MPa, respectively, between perpendicularly oriented samples). These results may simply reflect sample variability as no other obvious explanation is apparent (that is, other samples within these rock units showed little to no anisotropy from tensile testing).

Mode I Fracture Toughness Strength

The fracture toughness strength using the chevron bend (CB) method (with cylindrical-shaped samples) for four of the six rock units from Yosemite Valley (table 9, fig. 19) ranges from 0.75 (unit Kt) to 1.61 megapascal square root meters ($MPa\cdot m^{1/2}$) (unit Kec), with average values ranging from 0.79 (unit Kt) to 1.34 $MPa\cdot m^{1/2}$ (unit Khd). The fracture toughness strength using the cracked chevron notched Brazilian disk

Table 8. Brazilian tensile strength test results for six Yosemite Valley rock units.

[*L*, cylindrical sample length; *D*, cylindrical sample diameter; *P*, peak axial diametrical force applied to sample at failure; σ_t, tensile strength; mm, millimeters; kN, kilonewtons; MPa, megapascals; //, parallel; ⊥, perpendicular]

Sample number	Sample orientation[1]	*L* (mm)	*D* (mm)	*P* (kN)	σ_t (MPa)
El Capitan Granite (unit Kec)					
Kec-CS2	//	79.5	80.0	86.4	8.6
Kec-CS2	⊥	79.5	80.0	65.1	6.5
Kec-CS3	//	81.0	80.0	55.5	5.5
Kec-CS3	⊥	82.2	80.1	56.8	5.5
Tonalite of the Gray Bands (unit Kgb)					
Kgb-NT1	//	80.0	80.0	94.3	9.4
Kgb-NT1	⊥	80.0	80.1	66.8	6.6
Kgb-NT3	//	79.5	80.0	84.9	8.5
Taft Granite (unit Kt)					
Kt-RA1	//	80.2	80.0	71.1	7.1
Kt-RA1	⊥	80.1	80.0	78.1	7.8
Kt-RA2	//	84.0	80.0	55.4	5.2
Diorite of North America (unit Kd)					
Kd-ZT1	//	80.0	80.1	73.3	7.3
Kd-ZT1	⊥	80.0	80.1	76.5	7.6
Kd-ZT2	//	86.5	80.0	72.2	6.6
Sentinel Granodiorite (unit Ks)					
Ks-IC1	//	80.0	80.1	60.0	6.0
Ks-IC1	⊥	80.0	80.0	70.1	7.0
Ks-IC2	//	80.0	80.0	62.3	6.2
Ks-IC2	⊥	80.0	80.0	81.9	8.1
Half Dome Granodiorite (unit Khd)					
Khd-RP1	//	79.0	80.1	37.8	3.8
Khd-RP1	⊥	80.0	80.0	35.2	3.5
Khd-RP4	//	69.0	80.0	38.7	4.5
Khd-RP4	⊥	80.1	80.0	37.7	3.7
Khd-ML1	//	80.0	80.0	58.8	5.8
Khd-ML1	⊥	80.0	80.1	75.7	7.5

[1]//, test performed on sample cored parallel to any existing fabric (unit Ks only) or in an arbitrary direction (all other samples); ⊥, test performed on sample cored perpendicular to any existing fabric (unit Ks only) or perpendicular to the sample cored in an arbitrary direction (all other samples).

Table 9. Mode I fracture toughness results from chevron bend tests (K_{CB}) for four Yosemite Valley rock units.

[*L*, cylindrical sample length; *D*, cylindrical sample diameter; K_{CB}, mode I fracture toughness strength from chevron bend samples; mm, millimeters; t/m^3, metric tons per cubic meter; MPa·m$^{1/2}$, megapascal square root meters; //, parallel; ⊥, perpendicular]

Sample number	Chevron orientation[1]	*L* (mm)	*D* (mm)	Density (t/m^3)	K_{CB} (MPa·m$^{1/2}$)
El Capitan Granite (unit Kec)					
Kec-CS2	⊥	220.0	56.0	2.69	1.61
Kec-CS3	//	220.0	56.0	2.69	0.93
Kec-CS3	⊥	220.0	56.0	2.70	1.43
Taft Granite (unit Kt)					
Kt-RA1	//	220.0	56.0	2.59	0.75
Kt-RA3	//	220.0	56.0	2.62	0.83
Diorite of North America (unit Kd)					
Kd-ZT1	⊥	220.0	56.0	2.81	1.32
Half Dome Granodiorite (unit Khd)					
Khd-ML1a	//	220.0	56.0	2.65	1.36
Khd-ML1b	//	220.0	56.0	2.66	1.34
Khd-ML1c	//	220.0	56.0	2.66	1.32

[1]//, test performed on sample with chevron notch cut in an arbitrary direction; ⊥, test performed on sample with chevron notch cut perpendicular to the sample with notch cut in an arbitrary direction.

(CCNBD) method (with disk-shaped samples) for the six rock units from Yosemite Valley (table 10, fig. 20) ranges from 0.64 (unit Khd) to 1.60 MPa·m$^{1/2}$ (unit Ks), with average values ranging from 0.81 (unit Khd) to 1.32 MPa·m$^{1/2}$ (unit Kd). Tests performed on the same rock sample with the same orientation and the same testing method provided consistent results, with the three samples of Khd-ML having a standard deviation and coefficient of variation of only 0.02 MPa·m$^{1/2}$ and 1.2 percent, respectively. Results for all fracture toughness strength tests are provided in tables 9 and 10. Additional test results (force-displacement curves) and before and after testing photographs for each sample are provided in appendix 3 for CB-method results and appendix 4 for CCNBD-method results.

Comparison of similar individual samples between test type (that is, for the same rock sample and orientation between CB and CCNBD methods) reveals some variability, with CCNBD values differing by 14 percent (for samples Kec-CS3 parallel and Kd-ZT1 perpendicular) to as much as 41 percent (for sample Kec-CS3 perpendicular) compared to values obtained using the CB method (average 8 percent difference for all rock samples with the same orientation). Comparisons between tests for all samples within a single rock unit (using both parallel and perpendicularly oriented samples) provide similar results, with CCNBD average values differing by 0 (unit Kd) to 40 percent (unit Khd) (average 12 percent difference for all rock units) compared to CB average values. Some variations are expected, given the different testing methods, and are related to items such as the size of the specimens and anisotropy of the rock. However, important differences also exist between testing methods that may also yield different results; these include the dimensionless stress intensity factor parameter (that is, A_{min} and Y^*_{min}; see eqs. 4 and 5) used to calculate the fracture toughness (Iqbal and Mohanty, 2006; Erarslan, 2018) and the size of the fracture process zone during tensile failure (Wei and others, 2018). Because CCNBD-determined fracture toughness values tend to be conservative for design (that is, at the lower end of testing values; Iqbal and Mohanty, 2006; Erarslan, 2018; Wei and others, 2018) and therefore potentially more applicable for investigating rock-fall potential where failure can be imminent, and because we have CCNBD results for all rock units, we focus our presentation of the results on the values from these tests.

The rock units with the highest average CCNBD fracture toughness strength (units Kd, Kgd, and Ks) are the most mafic, containing an abundance of dark hornblende and biotite minerals compared to the other units tested. This suggests a link between these more mafic minerals and fracture toughness. A link between small grain size and high strength is only partly evident for the fracture toughness results. Whereas some rock units with small grain size (units Kgb and Kd) show increased strength compared to those with larger grain size (that is, units Kec and Khd; see fig. 20 and table 4), the Taft Granite (unit Kt) is anomalous in that its average fracture toughness is less than that for El Capitan Granite (Kec) despite

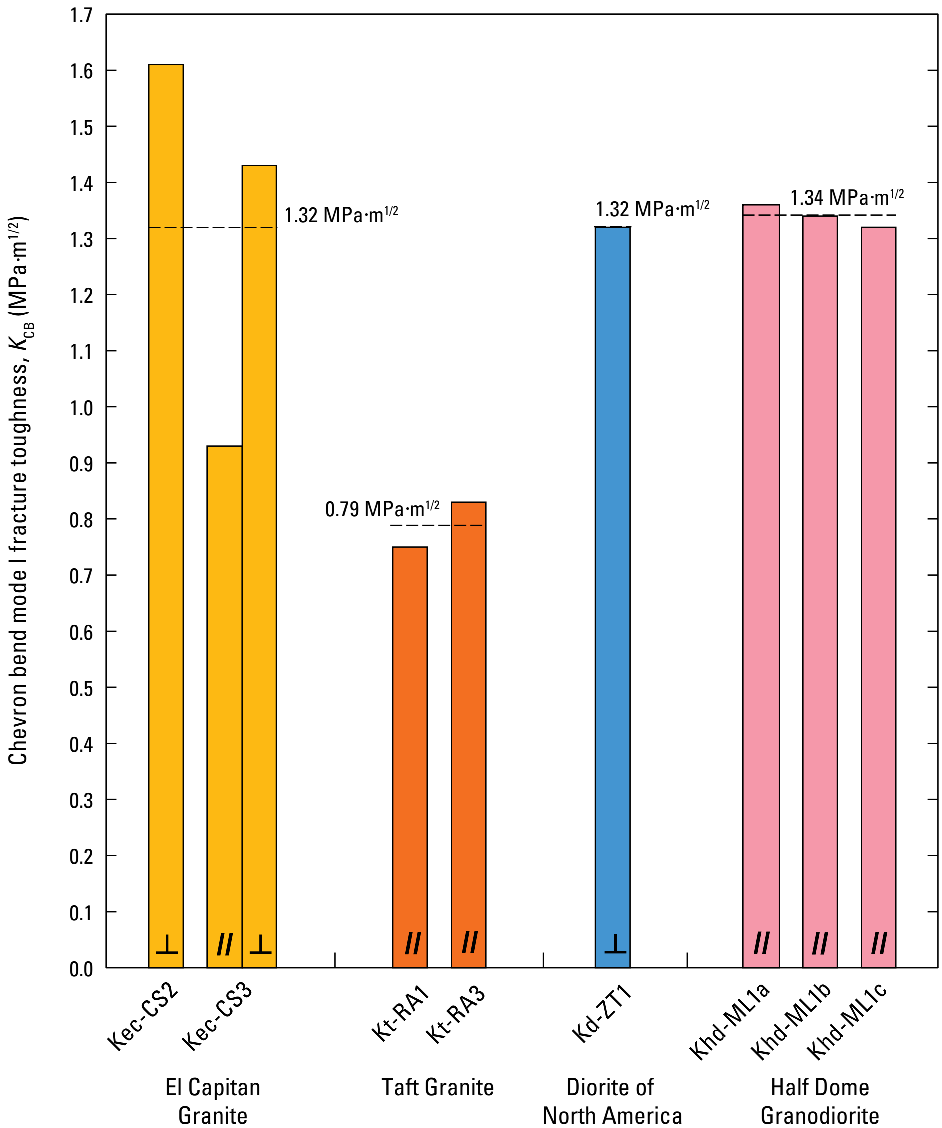


Figure 19. Plot of mode I fracture toughness chevron bend test results (in megapascal square root meters [MPa·m$^{1/2}$]) for four Yosemite Valley rock units. Average values for each unit are indicated by dashed horizontal black lines. //, parallel; ⊥, perpendicular.

Table 10. Mode I fracture toughness results from cracked chevron notched Brazilian disk tests (K_{IC}) for six Yosemite Valley rock units.

[*B*, cylindrical sample thickness; *D*, cylindrical sample diameter; Y^*_{min}, critical dimensionless stress intensity value; P_{max}, vertical load at failure; K_{IC}, mode I (tensile) fracture toughness from cracked chevron notched Brazilian disk (CCNBD) samples; mm, millimeters; kN, kilonewtons; MPa·m$^{1/2}$, megapascal square root meters; //, parallel; ⊥, perpendicular]

Sample number	Chevron orientation[1]	*B* (mm)	*D* (mm)	Initial crack length (mm)	Final crack length (mm)	Y^*_{min}	P_{max} (kN)	K_{IC} (MPa·m$^{1/2}$)
El Capitan Granite (unit Kec)								
Kec-CS2	//	30.4	80.0	13.0	23.8	0.7848	7.71	1.00
Kec-CS2	⊥	30.9	81.0	15.2	24.3	0.8103	8.44	1.10
Kec-CS3	//	30.8	79.9	12.3	23.8	0.7789	8.39	1.06
Kec-CS3	⊥	30.9	80.0	12.5	23.8	0.7781	6.71	0.85
Tonalite of the Gray Bands (unit Kgb)								
Kgb-NT1	//	30.2	79.5	13.8	24.2	0.8131	9.60	1.30

Table 10. Mode I fracture toughness results from cracked chevron notched Brazilian disk tests (K_{IC}) for six Yosemite Valley rock units.—Continued

Sample number	Chevron orientation[1]	B (mm)	D (mm)	Initial crack length (mm)	Final crack length (mm)	Y^*_{min}	P_{max} (kN)	K_{IC} (MPa·m$^{1/2}$)
Tonalite of the Gray Bands (unit Kgb)—Continued								
Kgb-NT1	⊥	30.9	80.0	13.3	24.0	0.7928	9.16	1.18
Kgb-NT2[2]	//	-	-	-	-	-	-	-
Kgb-NT2	⊥	30.9	80.2	13.3	24.2	0.7976	10.59	1.37
Kgb-NT3[2]	//	-	-	-	-	-	-	-
Kgb-NT3[3]	⊥	31.2	80.0	13.2	24.2	0.8002	6.39	0.82
Taft Granite (unit Kt)								
Kt-RA1	//	30.7	79.5	14.3	24.3	0.8181	7.47	1.00
Kt-RA1	⊥	30.7	80.0	11.4	23.8	0.7701	6.57	0.82
Kt-RA2	//	30.1	79.9	13.7	24.3	0.8120	5.99	0.81
Kt-RA2	⊥	30.9	80.0	10.1	24.6	0.7906	8.13	1.04
Diorite of North America (unit Kd)								
Kd-ZT1	//	30.4	80.0	13.5	24.0	0.7962	8.69	1.14
Kd-ZT1	⊥	30.1	80.0	12.5	24.1	0.7948	11.35	1.50
Kd-ZT2	//	30.5	80.2	13.5	24.2	0.7975	10.02	1.31
Kd-ZT2[2]	⊥	-	-	-	-	-	-	-
Sentinel Granodiorite (unit Ks)								
Ks-IC1	//	31.0	80.0	13.5	24.2	0.8002	7.20	0.93
Ks-IC1	⊥	30.7	79.9	12.9	24.3	0.7968	7.71	1.00
Ks-IC2	//	31.6	80.0	12.8	24.3	0.7963	11.28	1.43
Ks-IC2	⊥	30.9	80.0	12.9	24.2	0.7923	12.48	1.60
Half Dome Granodiorite (unit Khd)								
Khd-RP1	//	30.1	79.9	11.5	23.7	0.7745	4.95	0.64
Khd-RP1	⊥	30.0	81.0	14.6	24.3	0.8086	5.16	0.69
Khd-RP4	//	31.1	80.0	12.0	24.3	0.7919	5.05	0.64
Khd-RP4	⊥	30.9	80.0	12.4	24.0	0.7849	5.32	0.68
Khd-ML1	//	31.1	80.0	12.0	24.3	0.7919	8.79	1.12
Khd-ML1	⊥	30.8	80.0	13.4	24.0	0.7928	8.32	1.07

[1]//, test performed on sample with chevron notch cut parallel to any existing fabric (all samples of unit Ks and sample Kgb-NT2 only) or in an arbitrary direction (all other samples); ⊥, test performed on sample with chevron notch cut perpendicular to any existing fabric (all samples of unit Ks and sample Kgb-NT2 only) or perpendicular to the sample with notch cut in an arbitrary direction (all other samples).

[2]The core length for directional testing in these samples was insufficient from the blocks collected in the field and these tests could not be performed.

[3]An undetected defect in the CCNBD rock disk prior to testing is likely responsible for the low strength of this sample (see photographs in appendix 4). It is not used in calculation of average fracture toughness strength for the tonalite of the Gray Bands (unit Kgb).

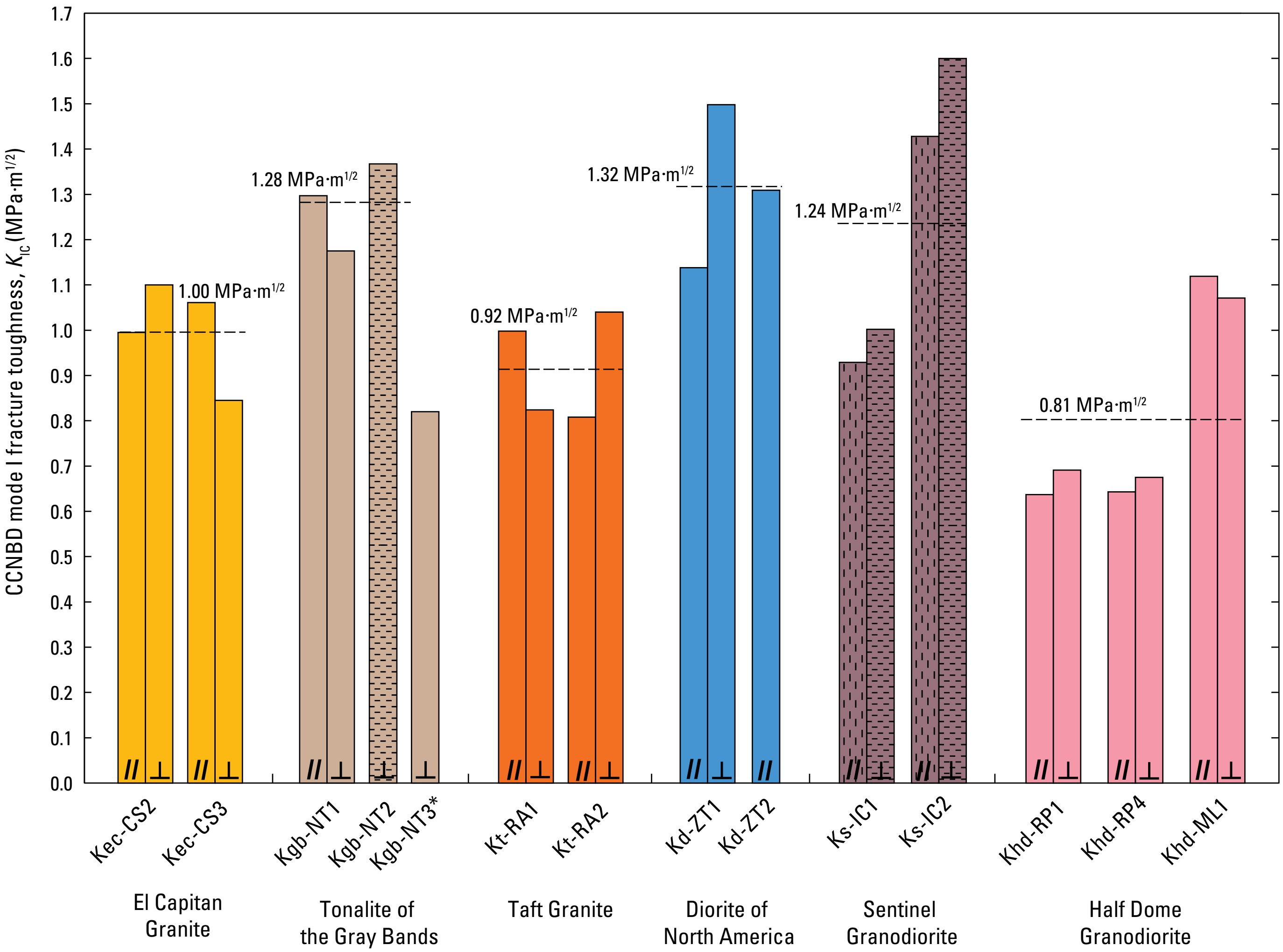


Figure 20. Plot of mode I fracture toughness cracked chevron notched Brazilian disk (CCNBD) test results (in megapascal square root meters [MPa·m^1/2]) for six Yosemite Valley rock units. Average values for each unit are indicated by dashed horizontal black lines. Denoted by an asterisk, the low fracture toughness of sample Kgb-NT3 is likely due to a previously undetected flaw in the CCNBD rock disk for this sample; its value is not used in calculation of the average strength reported for the tonalite of the Gray Bands (unit Kgb). For Sentinel Granodiorite (unit Ks) and one tonalite of the Gray Bands (unit Kgb) samples, patterns show the rock fabric. //, parallel; ⊥, perpendicular.

the Taft Granite having lower average and maximum grain size (table 4). This result is corroborated by the CB fracture toughness results (fig. 19) and might indicate a true weakness in the fracture toughness of this rock unit.

The rock unit with the lowest average fracture toughness is the Half Dome Granodiorite (unit Khd), consistent with the larger grain size and lower values for strength (compared to other rock units) also obtained via unconfined compression strength and Brazilian tensile strength testing (see figs. 11 and 18). The range of fracture toughness values within rock units show some signs of homogeneity—coefficients of variation are on the order of 10–11 (units Kec, Kt, and Kd) to 26 percent (unit Khd) for the K_{IC} results. In one sample (Kgb-NT3), a defect in the CCNBD rock disk (see photographs in appendix 4) is visible prior to testing and is likely responsible for the low strength obtained for this sample compared to other tests of the tonalite of the Gray Bands (unit Kgb). Similar to the Brazilian tensile test results, the increased variability of the Half Dome Granodiorite (unit Khd) may be indicative of the different source locations from which the samples were collected (that is, from Royal Prerogative Flake and Mirror Lake; fig. 4).

The influence of fabric on fracture toughness is evident for the strongest foliated rock tested (unit Ks). Here, the Sentinel Granodiorite shows a 7 to 10 percent reduction in strength in the parallel versus perpendicularly oriented direction. For other rock units, some anisotropy is also evident (for example, the 20–25 percent differences in perpendicularly oriented samples of units Kt and Kd; fig. 20), but cannot be confirmed because of the lack of visible fabric in these samples.

Summary

We performed a total of 88 tests on six of the major geologic units that form the cliffs of Yosemite Valley, California (table 11). These tests covered a range of geomechanical rock strength parameters, including those obtained by compression, shear, tension, and fracture modes of failure. Although variability exists within rock units, some overall trends are apparent. In general, rock units with small grain size, high density, and more mafic minerology (that is, units Kd, Ks, and Kgb) are strong in tension (tables 12, 13), whereas rock units with large grain size (for example, units Khd and Kec) are generally weak in tension. Furthermore, the Half Dome Granodiorite (unit Khd) is one of the weaker rock units overall, with relatively low strength values in both compression and tension. In shear, the Taft Granite (unit Kt) is generally stronger, whereas the Sentinel Granodiorite (unit Ks) is generally weaker (table 13, fig. 16). We expect that the results presented herein will assist with future research in Yosemite Valley with respect to both rock mechanics studies, such as those focused on rock falls, as well as more generalized geomorphology studies, such as those aimed at understanding the rates of fluvial and glacial erosion, long-term granitic weathering, and the evolution of cliffs and talus deposits throughout Yosemite Valley.

Table 11. Number of rock mechanics tests performed on six rock units in Yosemite Valley.

[CB, chevron bend; CCNBD, cracked chevron notched Brazilian disk]

Geologic unit	Unconfined compressive strength	Triaxial compressive strength	Brazilian tensile strength	Mode I fracture toughness (CB)	Mode I fracture toughness (CCNBD)	Total
El Capitan Granite (unit Kec)	3	2	4	3	4	16
Tonalite of the Gray Bands (unit Kgb)	3	2	3	-	4	12
Talf Granite (unit Kt)	3	2	3	2	4	14
Diorite of North America (unit Kd)	3	2	3	1	3	12
Sentinel Granodiorite (unit Ks)	3	2	4	-	4	13
Half Dome Granodiorite (unit Khd)	4	2	6	3	6	21
Total	19	12	23	9	25	88

Table 12. Summary of rock mechanics strength properties for six rock units in Yosemite Valley.

[Average values are listed for all test values. Minimum and maximum values are listed in parentheses. σ_c, unconfined compressive strength; E_{50}, elastic modulus at 50 percent strain; v, Poisson's ratio; ϕ_{res}, residual friction angle; c_{res}, residual cohesion; ϕ_{peak}, peak friction angle; c_{peak}, peak cohesion; σ_t, tensile strength; K_{IC}, mode I (tensile) fracture toughness strength; t/m^3, metric tons per cubic meter; MPa, megapascals; GPa, gigapascals; MPa·m$^{1/2}$, megapascal square root meters]

Geologic unit symbol	Density (t/m^3)	σ_c (MPa)	E_{50}[1] (GPa)	v	ϕ_{res} (degrees)	c_{res} (MPa)	ϕ_{peak}[2] (degrees)	c_{peak}[2] (MPa)	σ_t (MPa)	K_{IC}[3] (MPa·m$^{1/2}$)
Kec	2.68 (2.62–2.70)	137 (111–171)	30.1 (24.6–37.1)	0.22 (0.20–0.25)	52 (48–56)	1.4 (0.3–2.5)	62	15.4	6.5 (5.5–8.6)	1.14 (0.85–1.61)
Kgb[4]	2.75 (2.72–2.78)	130 (120–137)	32.8 (25.5–38.9)	0.21 (0.18–0.22)	52 (51–53)	1.3 (0.9–1.7)	62	15.0	8.2 (6.6–9.4)	1.28 (1.18–1.37)
Kt	2.61 (2.59–2.63)	149 (136–160)	29.8 (24.4–34.3)	0.23 (0.20–0.27)	53 (51–55)	1.7 (0.6–2.8)	59	22.2	6.7 (5.2–7.8)	0.88 (0.75–1.04)
Kd	2.82 (2.80–2.88)	149 (116–190)	35.4 (26.7–52.6)	0.11 (0.06–0.16)	49 (48–50)	1.5 (0.6–2.4)	51	25.6	7.2 (6.6–7.6)	1.32 (1.14–1.50)
Ks[5]	2.77 (2.76–2.79)	118 (79–119)	31.1 (20.0–44.4)	0.22 (0.19–0.40)	48 (45–51)	1.5 (0.6–2.4)	58	12.5	6.8 (6.0–8.1)	1.24 (0.93–1.60)
Khd[5,6]	2.66 (2.64–2.73)	124 (92–130)	34.0 (22.2–37.3)	0.20 (0.16–0.39)	49 (46–52)	2.9 (2.4–3.4)	75 (71–79)	6.6 (4.2–9.0)	4.8 (3.5–7.5)	0.98 (0.64–1.36)

[1]E_{50} values are the average from the unconfined and triaxial test results.

[2]Only one set of peak shear strength values is listed for each rock unit, with the exception of unit Khd, where results from two different sets of samples (RP2 and ML1) were tested.

[3]K_{IC} values are the average from the mode I fracture toughness test results for both chevron bend (CB) and cracked chevron notched Brazilian disk (CCNBD) samples.

[4]Average and minimum values of K_{IC} for the tonalite of the Gray Bands (unit Kgb) do not include the anomalously low value from sample Kgb-NT3 that resulted from a previously undetected flaw in the CCNBD rock disk prior to testing.

[5]Average values of σ_c, E_{50}, and v for the Sentinel Granodiorite (unit Ks) and Half Dome Granodiorite (unit Khd) do not include results from samples Ks-IC3 and Khd-RP4 because of the different initial loading conditions experienced for these samples under unconfined compressive strength testing.

[6]Values of ϕ_{peak} and c_{peak} for the Half Dome Granodiorite (unit Khd) represent low confining stresses (0 to 1 MPa) and are therefore not comparable to results from other rock units tested at higher confinement (0 to 3 MPa).

Table 13. Comparison of ranked values of rock strength properties for six rock units in Yosemite Valley.

[Geologic unit symbols are as defined in table 1. σ_c, unconfined compressive strength; E_{50}, elastic modulus at 50 percent strain; v, Poisson's ratio; ϕ_{res}, residual friction angle; c_{res}, residual cohesion; ϕ_{peak}, peak friction angle; c_{peak}, peak cohesion; σ_t, tensile strength; K_{IC}, mode I (tensile) fracture toughness strength]

Rank	Density	Compression			Shear[1]				Tension	
		σ_c	E_{50}	v	ϕ_{res}	c_{res}	ϕ_{peak}	c_{peak}	σ_t	K_{IC}
1 (high)	Kd	Kt, Kd	Kd	Kt	Kt	Khd	Kec, Kgb	Kd	Kgb	Kd
2	Ks	Kec	Khd	Kec, Ks	Kec, Kgb	Kt	Kt	Kt	Kd	Kgb
3	Kgb	Kgb	Kgb	Kgb	Kd, Khd	Kd, Ks	Ks	Kec	Ks	Ks
4	Kec	Khd	Ks	Khd	Ks	Kec	Kd	Kgb	Kt	Kec
5	Khd	Ks	Kec	Kd		Kgb		Ks	Kec	Khd
6 (low)	Kt		Kt						Khd	Kt

[1]Ranking of the Half Dome Granodiorite (unit Khd) for ϕ_{peak} and c_{peak} are not shown owing to incompatible comparison with other rock units. See table 12.

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Appendixes 1–4

Appendix 1. Unconfined Compressive Strength Test Results and Sample Photographs

This appendix contains the stress-strain results and before and after photographs for each of the 19 unconfined compressive strength tests performed on the Yosemite Valley rock samples. Because the testing was performed at the French-speaking Laboratoires de Mecanique des Sols et des Roches (Soil and Rock Mechanics Laboratory) at the École Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology Lausanne, EPFL) in Lausanne, Switzerland, the data sheets containing the results are in French. A key to pertinent information contained on these forms is included here. Note that the Swiss Standard Testing Procedure SN 670 353 referenced in the test results is equivalent to the most recent standard (2019 Swiss National Standard VSS-70353A) referenced in the report. Note also that "Ep50%" is equivalent to E_{50} as used in the main text of this report.

SOIL AND ROCK MECHANICS LABORATORY

UNIAXIAL COMPRESSION

Executed according to the standard SN 670 353 and LMS+R ER.520

Sample Number	Title of the Study	Client	
		Name	Address
R0839-Kec-CS1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

Borehole Number	Depth [m]	Sample description	Sample collected by	Date received	Date tested
Kec	-	EL CAPITAN GRANITE	Client	08.07.14	26.08.14

Sample storage method	Sample preparation method	Engineer in charge		Operator
		Name	Signature	
NATURAL	SCIE, RECTIFIE	F. SANDRONE		LG

Height [mm]	Diam. [mm]	ρ [t/m³]	w [%]	σ_c [MN/m²]	Ep50% [MN/m²]	$E_{recharge}$ [MN/m²]	ν
109.2	56.0	2.64	-	129.6	31100	-	0.22

French

Contrainte [MN/m²]
Deformation, ε_1, ε_3
Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée. En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais."

English

Stress [MPa]
Strain, ε_1, ε_3
These test results cannot be perfectly reproduced and only apply to the sample tested. In addition, the results are part of a series of tests—see the test report page.

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

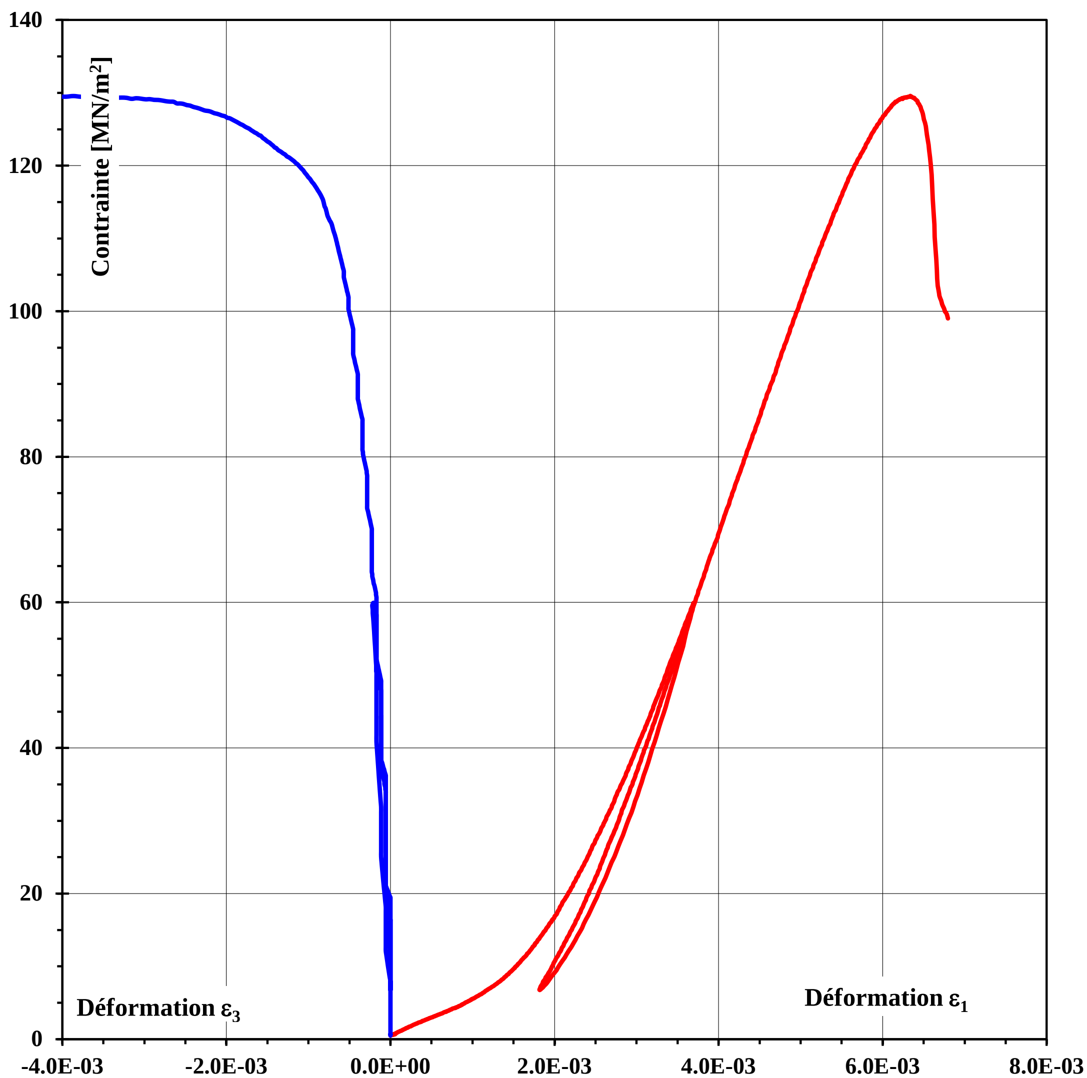
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kec-CS1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
109.2	56.0	2.64	-	129.6	31100	-	0.22



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

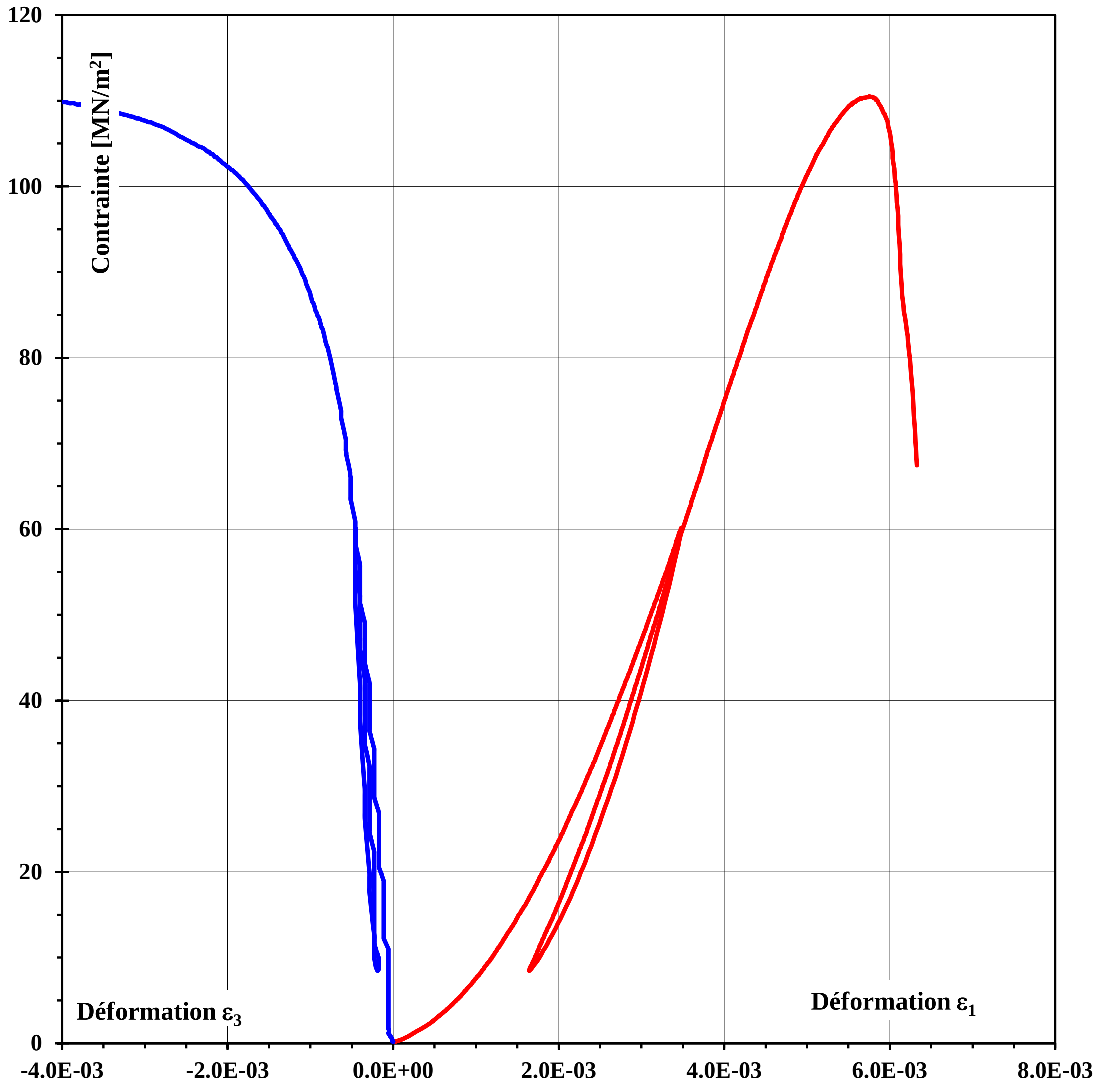
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Kec-CS3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
116.4	55.7	2.70	-	110.5	26700	-	0.20



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

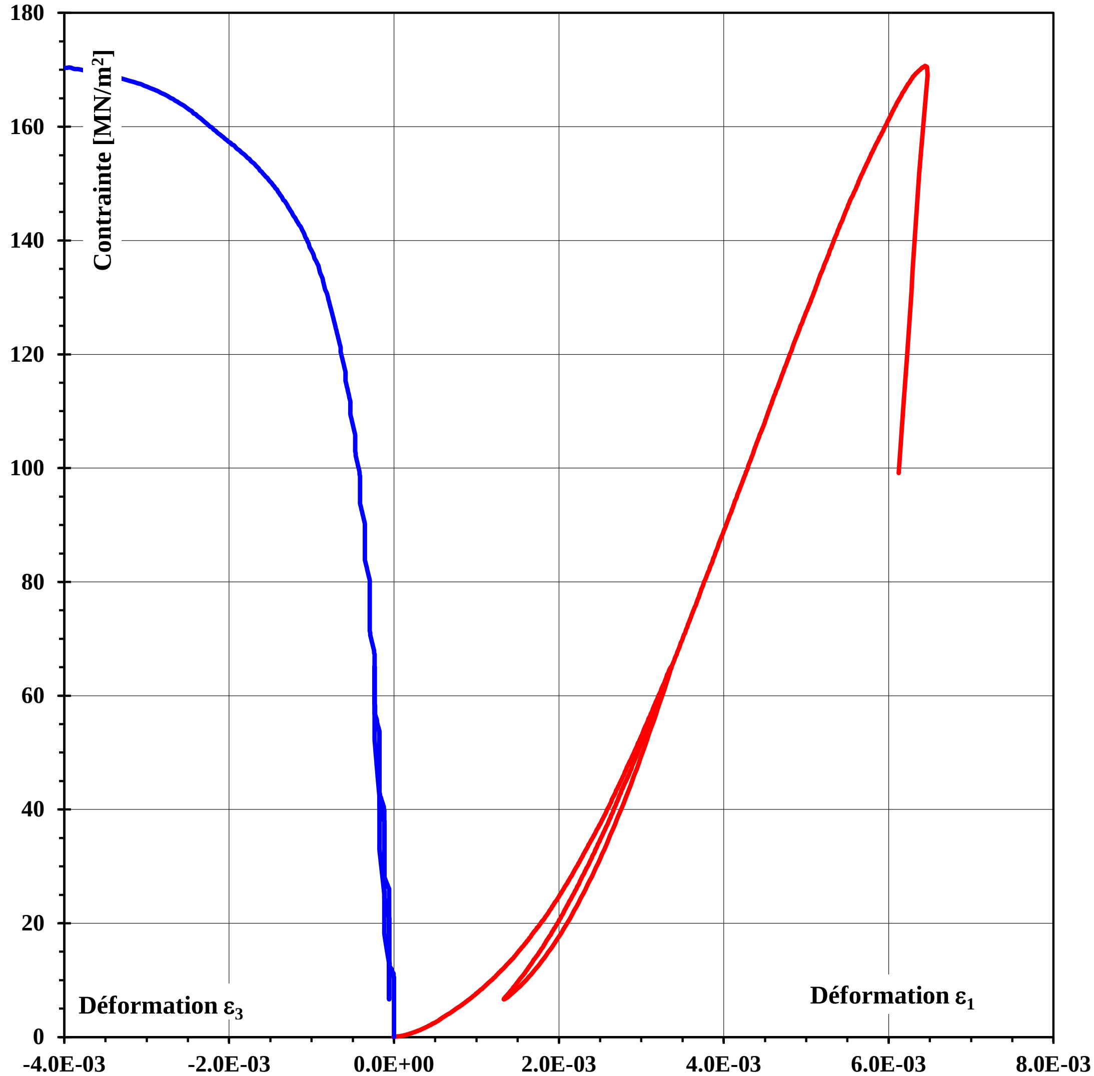
COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette		Titre de l'étude	Commettant		
			nom		adresse
R0839-Kec-CS4		ESSAIS UNIL-USGS	UNIL		LAUSANNE
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	26.08.14
Mode conservation		Mode préparation éprouvette	Ingénieur responsable		Opérat.
			nom	signature	
NATUREL		SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m³]	w [%]	σ_c [MN/m²]	Ep50% [MN/m²]	$E_{recharge}$ [MN/m²]	ν
116.5	54.1	2.62	-	170.7	37100	-	0.25



Observations:

LMS-LMR 75 ANS 1935-2010

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

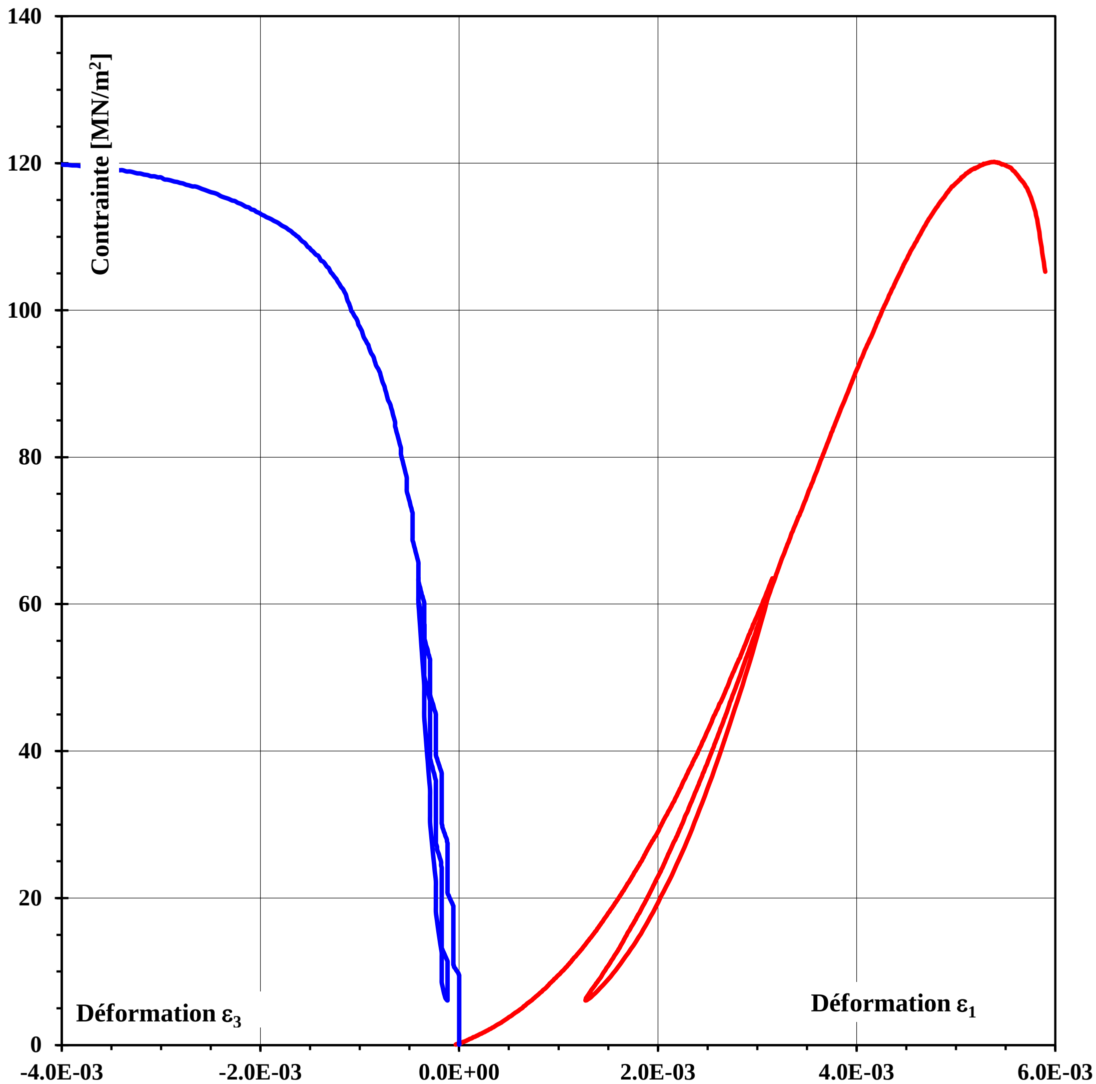
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kgb-NT1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE	[signature]	LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
117.1	54.3	2.78	-	120.2	34100	-	0.18



Observations:

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En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

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COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

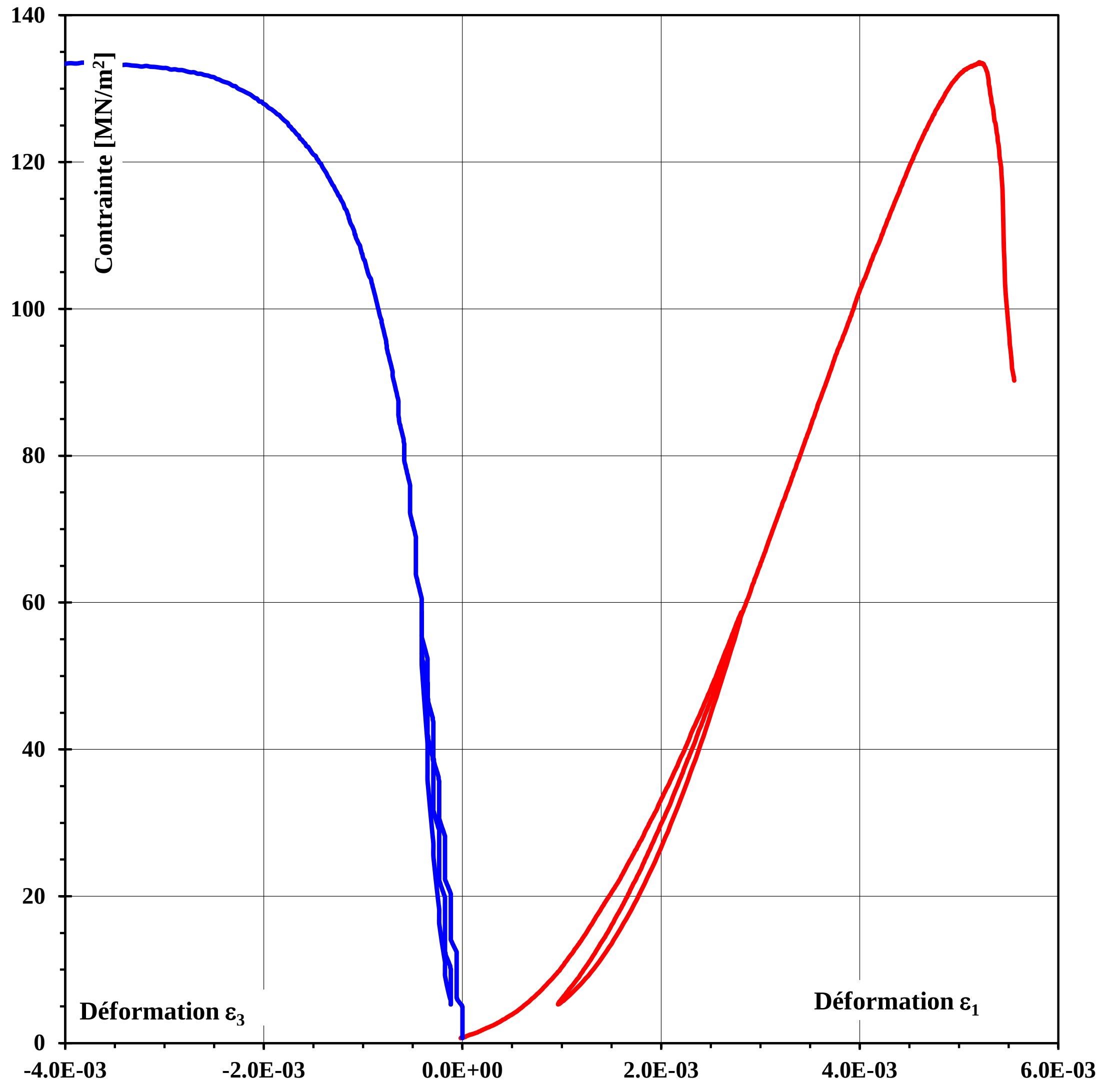
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kgb-NT2	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
118.8	54.3	2.74	-	133.6	35900	-	0.22



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

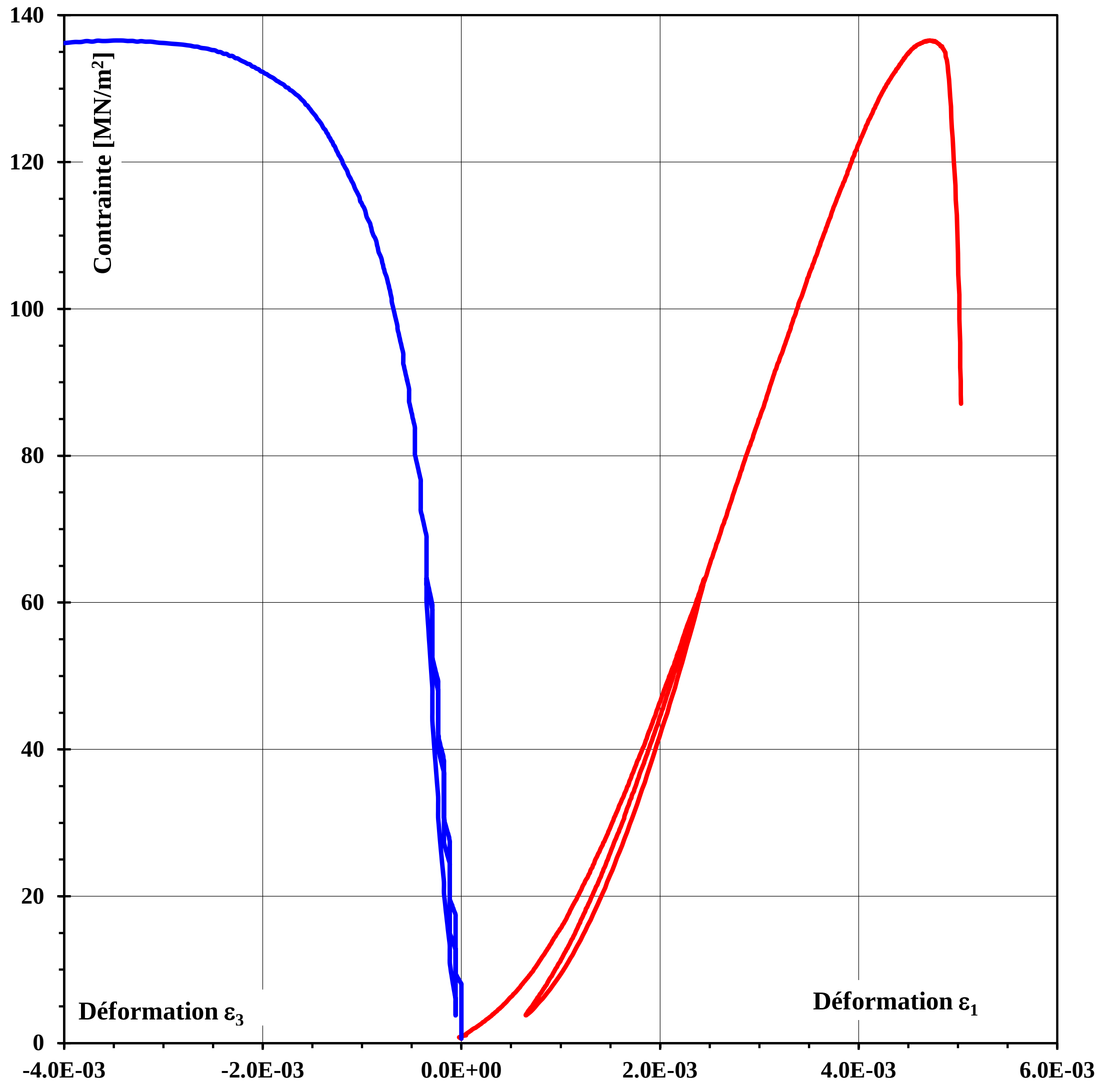
Exécuté selon la norme SN 670 353 et LMS+R ER.520

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kgb-NT3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
117.4	54.4	2.73	-	136.6	38900	-	0.22



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

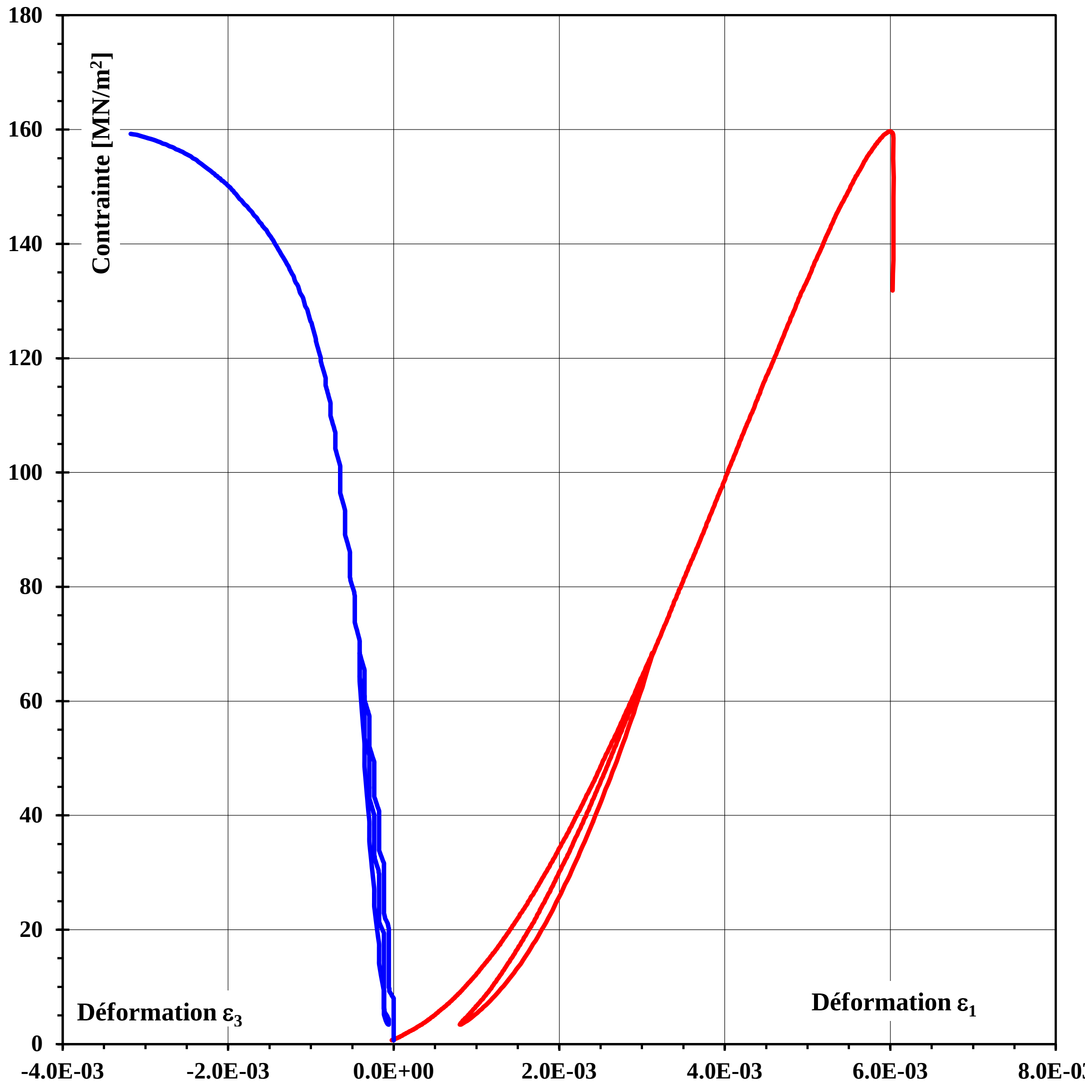
Exécuté selon la norme SN 670 353 et LMS+R ER.520

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette		Titre de l'étude	Commettant		
			nom		adresse
R0839-Kt-RA1		ESSAIS UNIL-USGS	UNIL		LAUSANNE
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE	[signature]	LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
116.4	54.2	2.62	-	159.7	34300	-	0.23



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

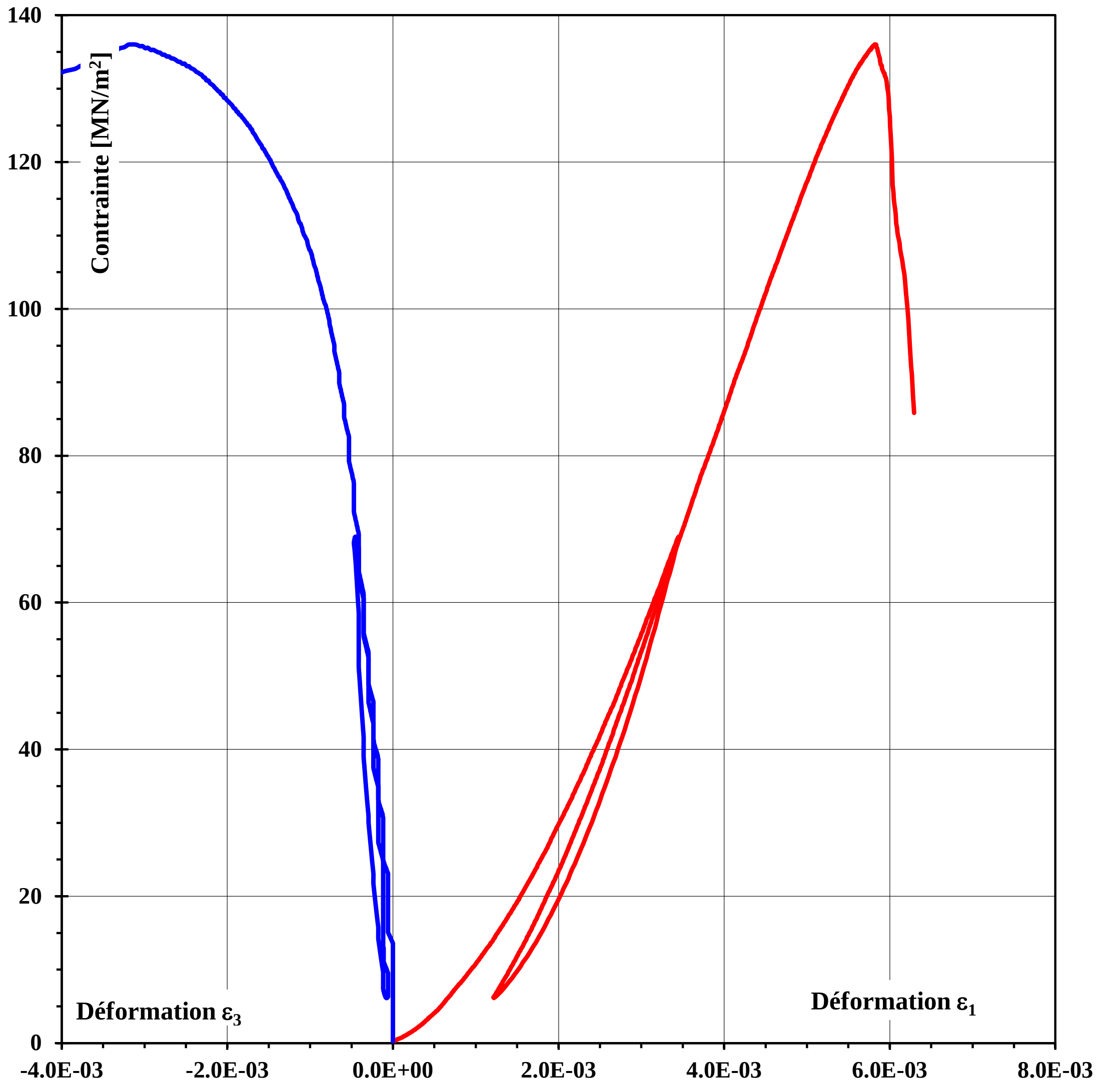
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Kt-RA3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m³]	w [%]	σ_c [MN/m²]	Ep50% [MN/m²]	$E_{recharge}$ [MN/m²]	ν
115.9	54.0	2.63	-	136.0	31100	-	0.27



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LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

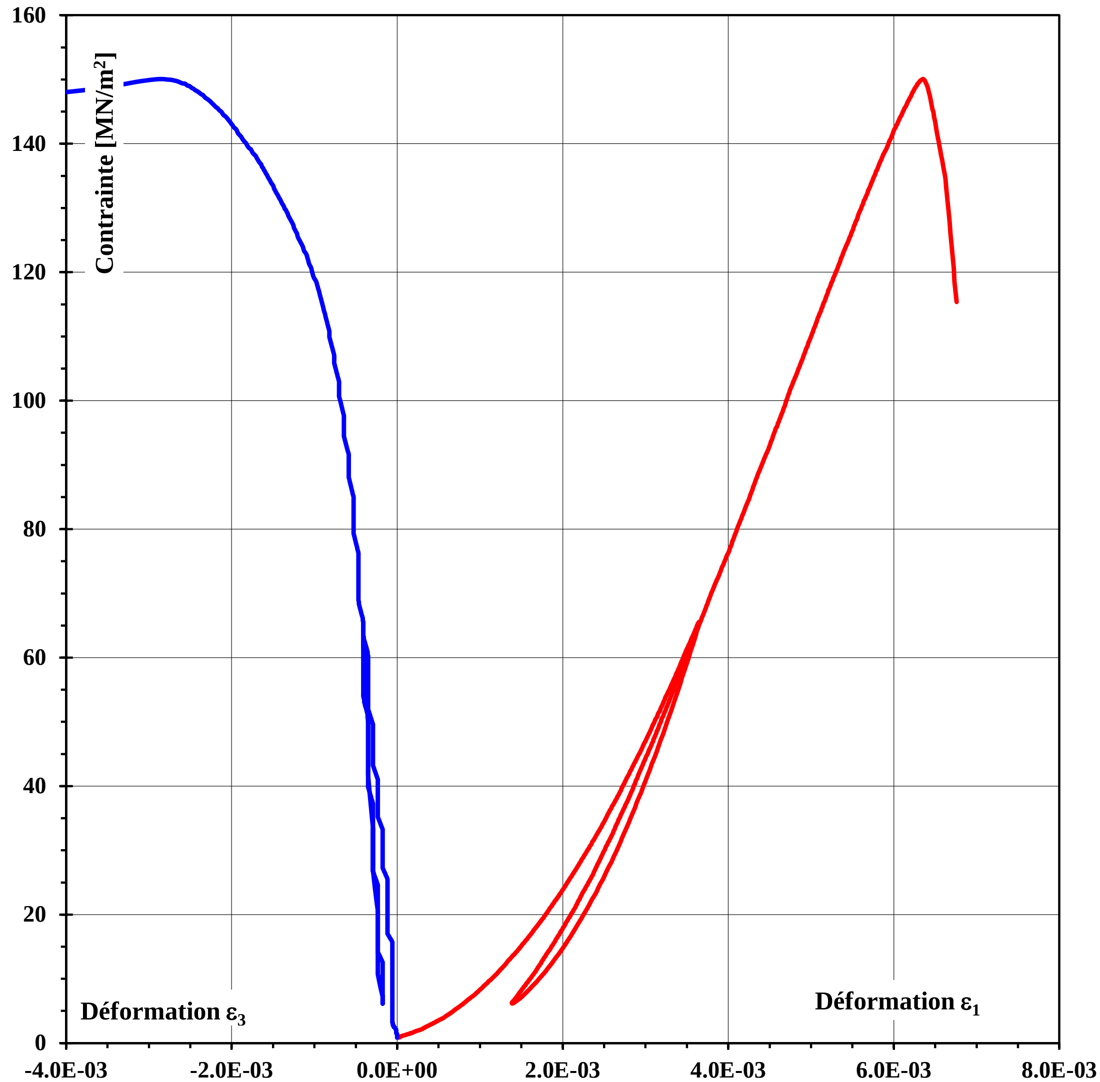
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kt-RA4	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
115.9	54.4	2.59	-	150.1	32600	-	0.20



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

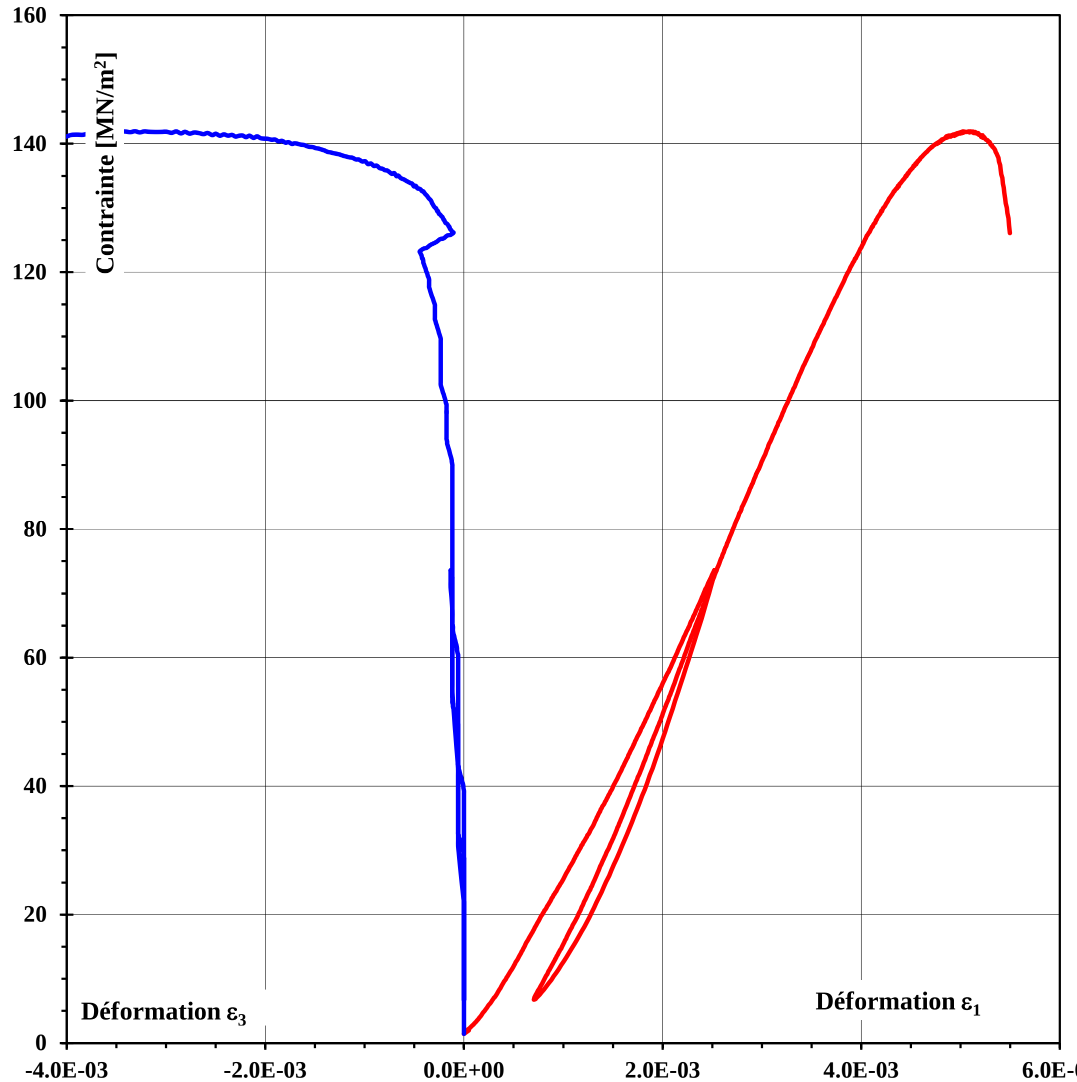
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kd-ZT1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
116.8	54.4	2.81	-	141.9	35600	-	0.06



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

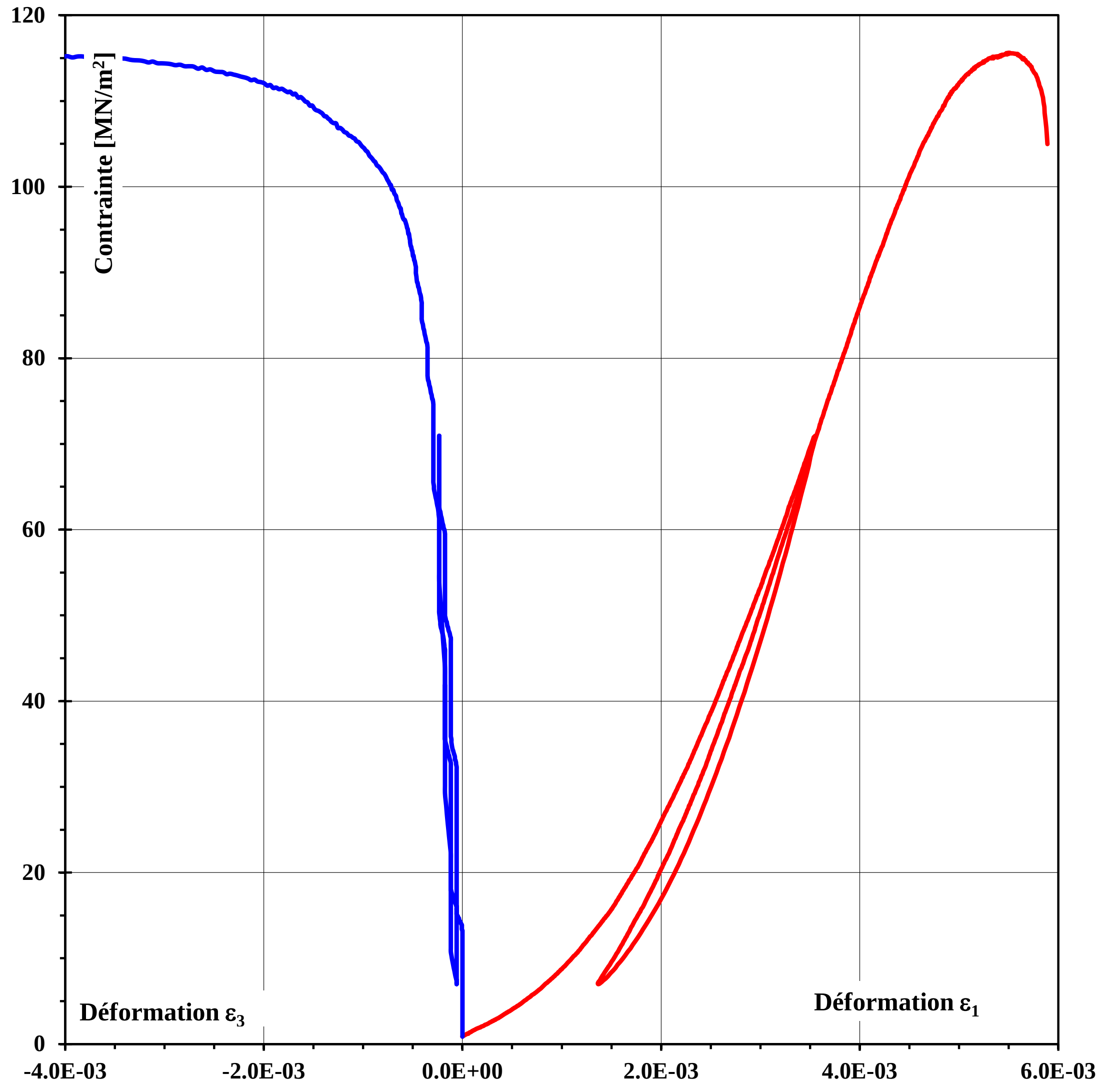
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Kd-ZT3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
116.7	54.3	2.80	-	115.6	32400	-	0.11



Observations:

LMS-LMR 75 ANS 1935-2010

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

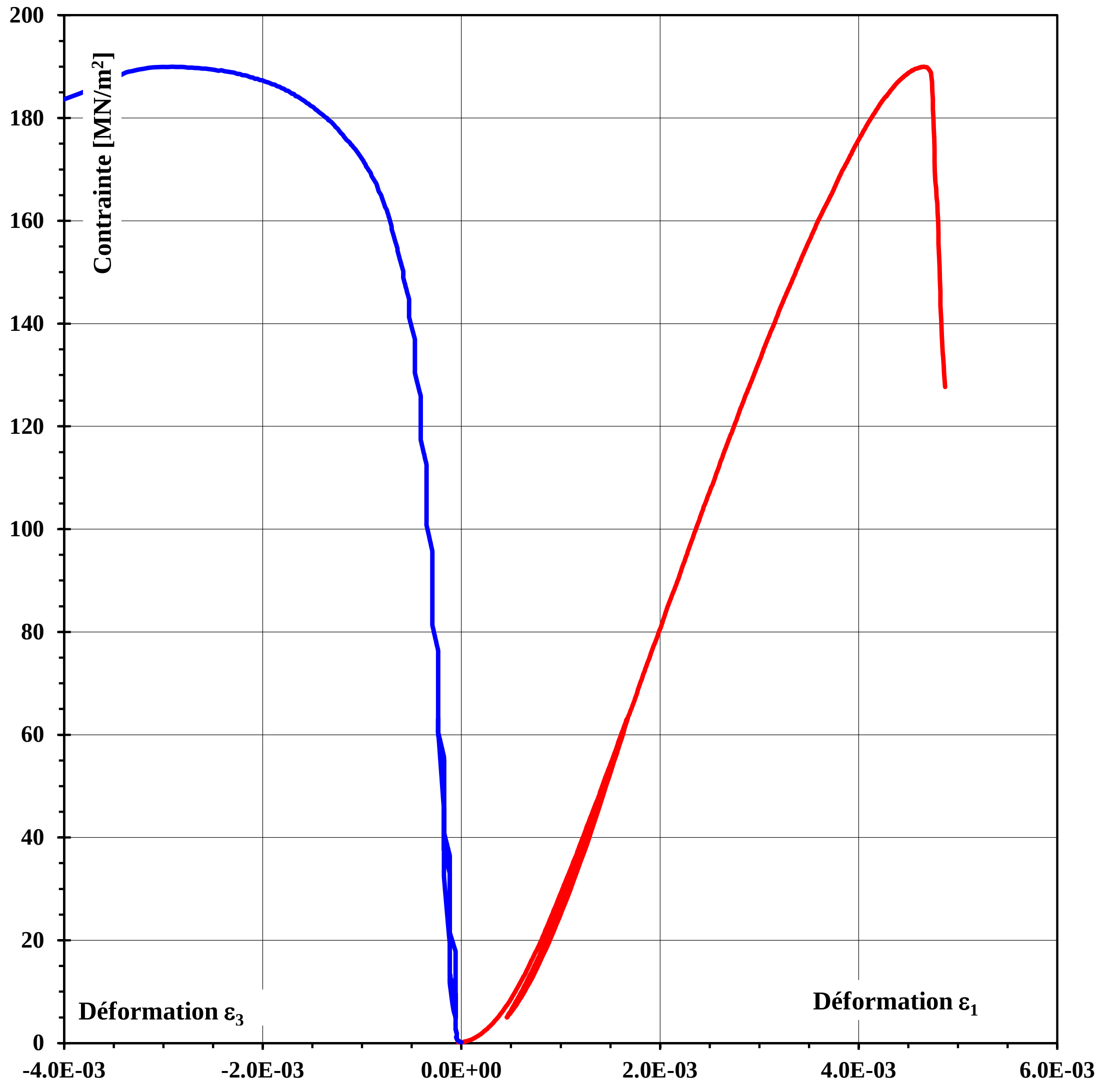
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kd-ZT4	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE	[signature]	LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
115.8	54.4	2.88	-	190.0	52600	-	0.16



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée
En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

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R0839-Kd-ZT4_Cs.xlsx

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

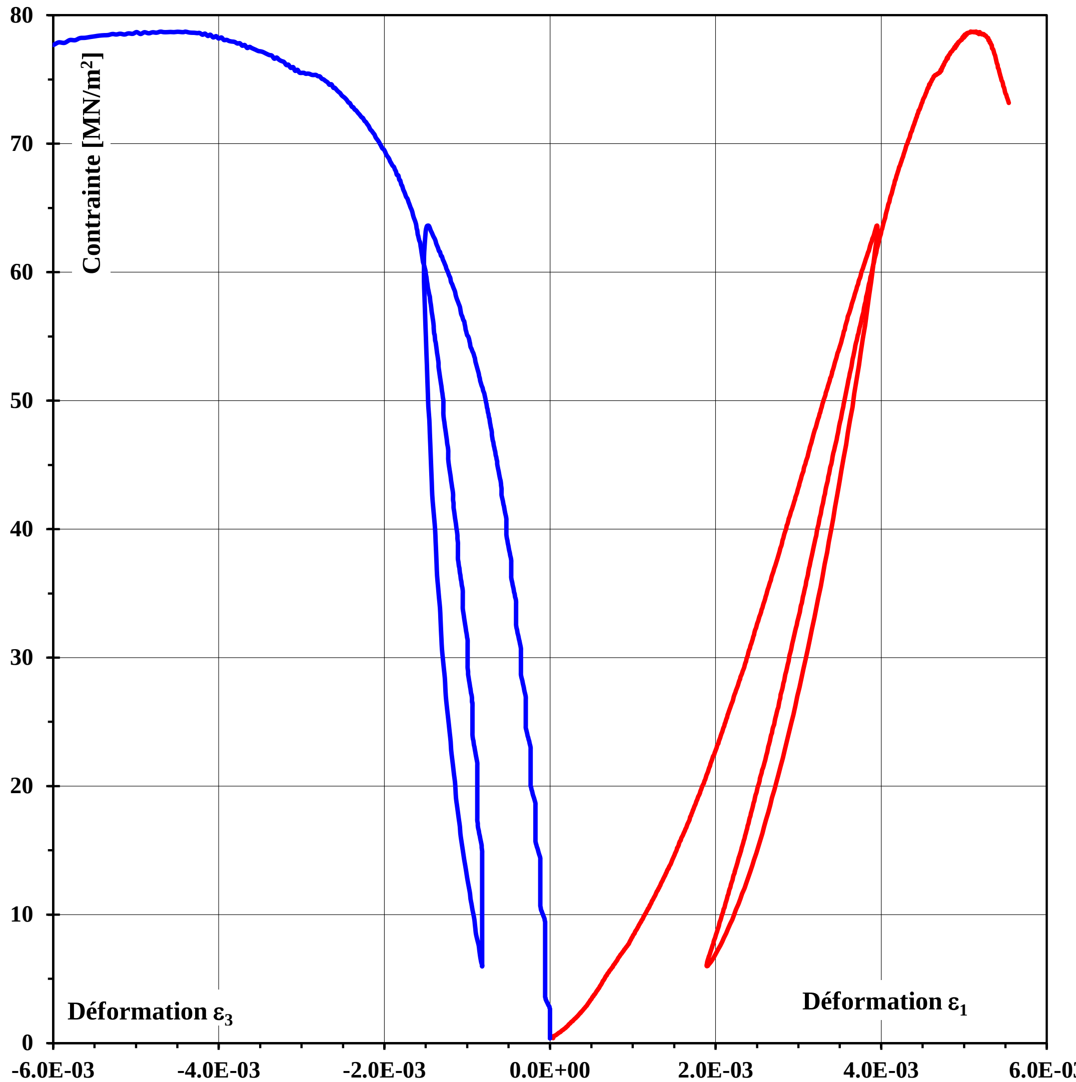
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Ks-IC3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
118.8	54.4	2.77	-	78.7	21300	30800	0.40



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

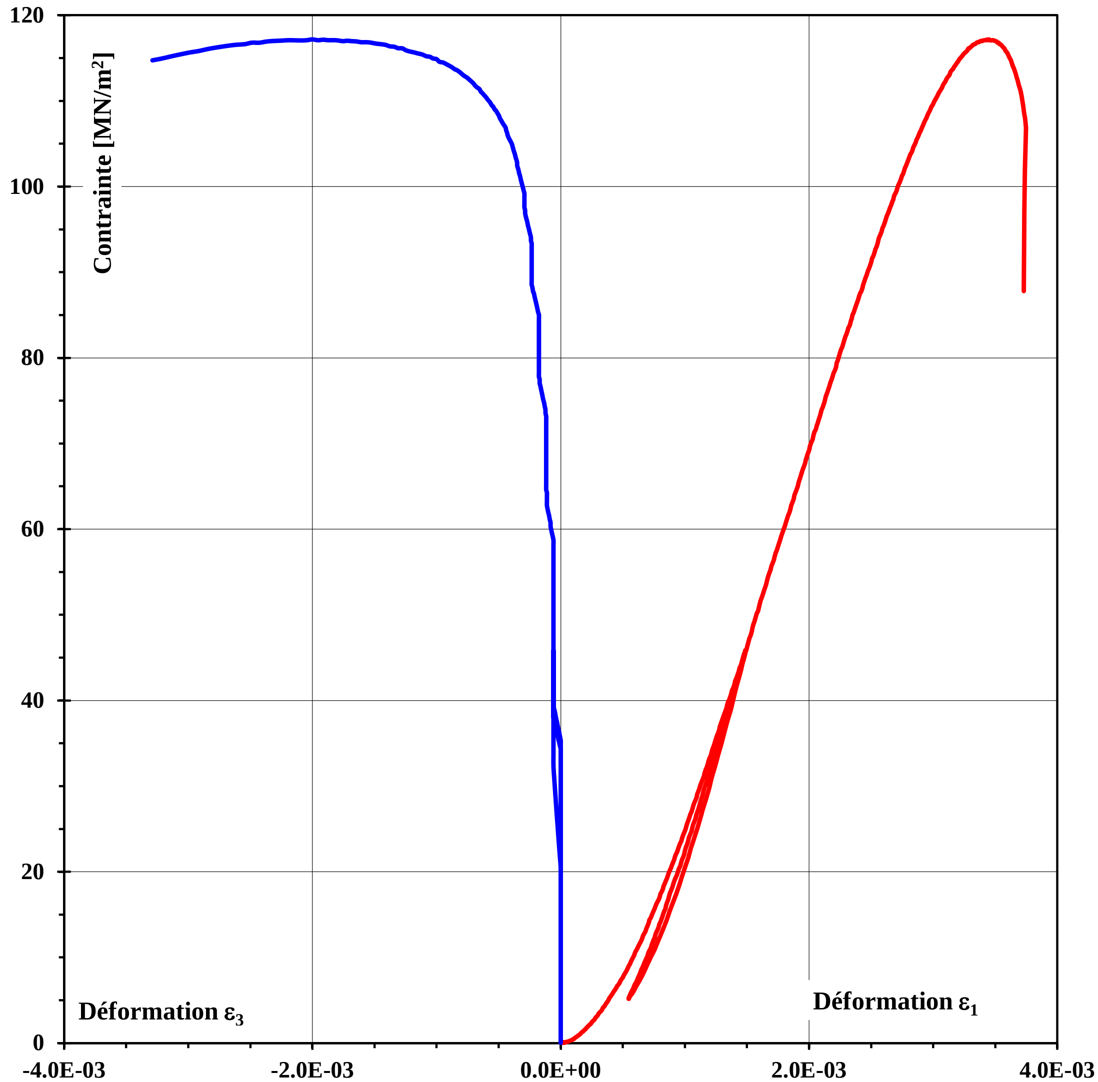
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Ks-IC4	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
119.3	54.4	2.79	-	117.2	44400	-	0.19



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

LMS-LMR 75 ANS 1935-2010

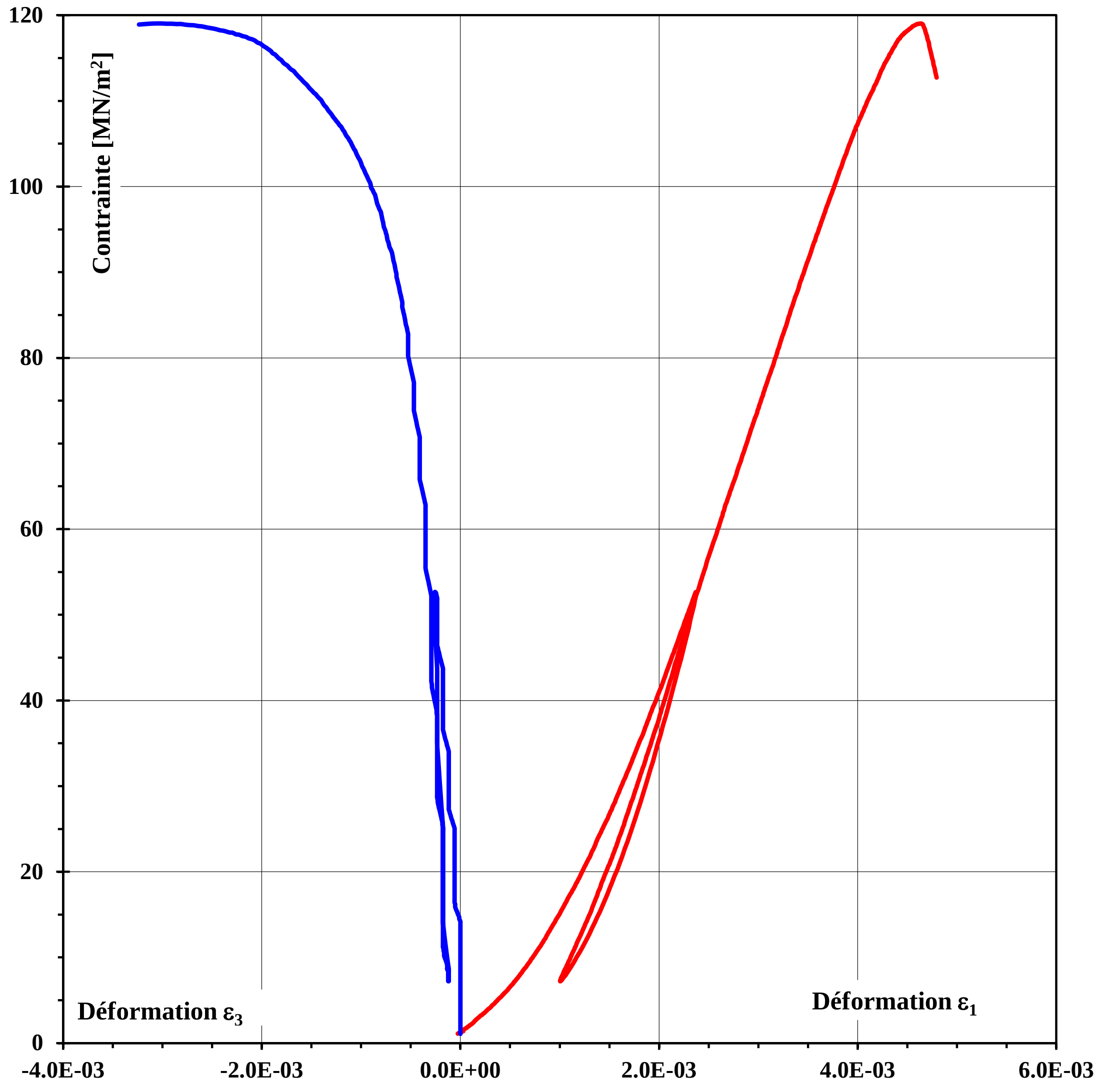
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Ks-IC5	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
119.4	54.4	2.78	-	119.0	35300	-	0.24



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

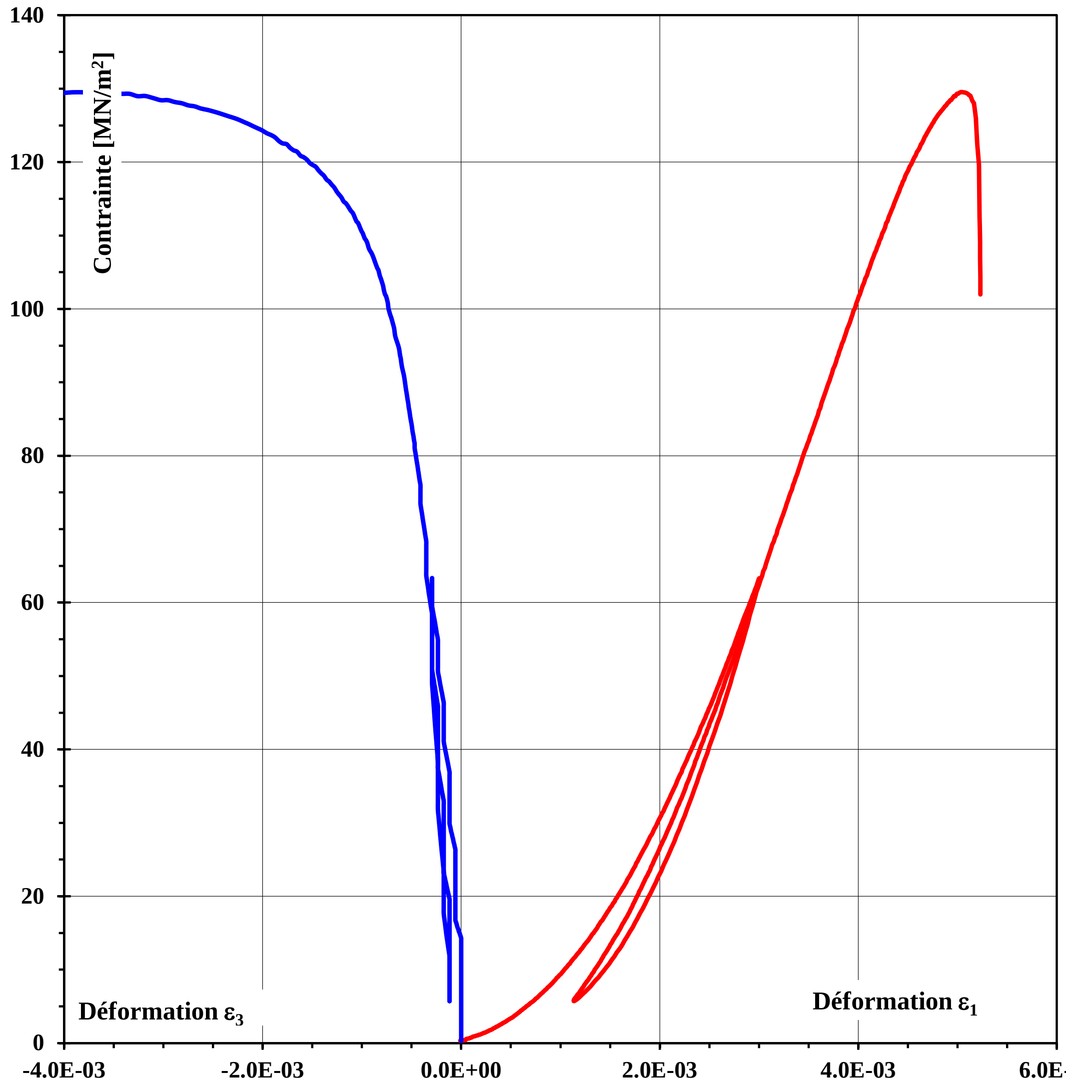
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant: nom	Commettant: adresse
R0839-Khd-RW1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable: nom	Ingénieur responsable: signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
117.5	54.3	2.73	-	129.5	37300	-	0.23



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

LMS-LMR 75 ANS 1935-2010

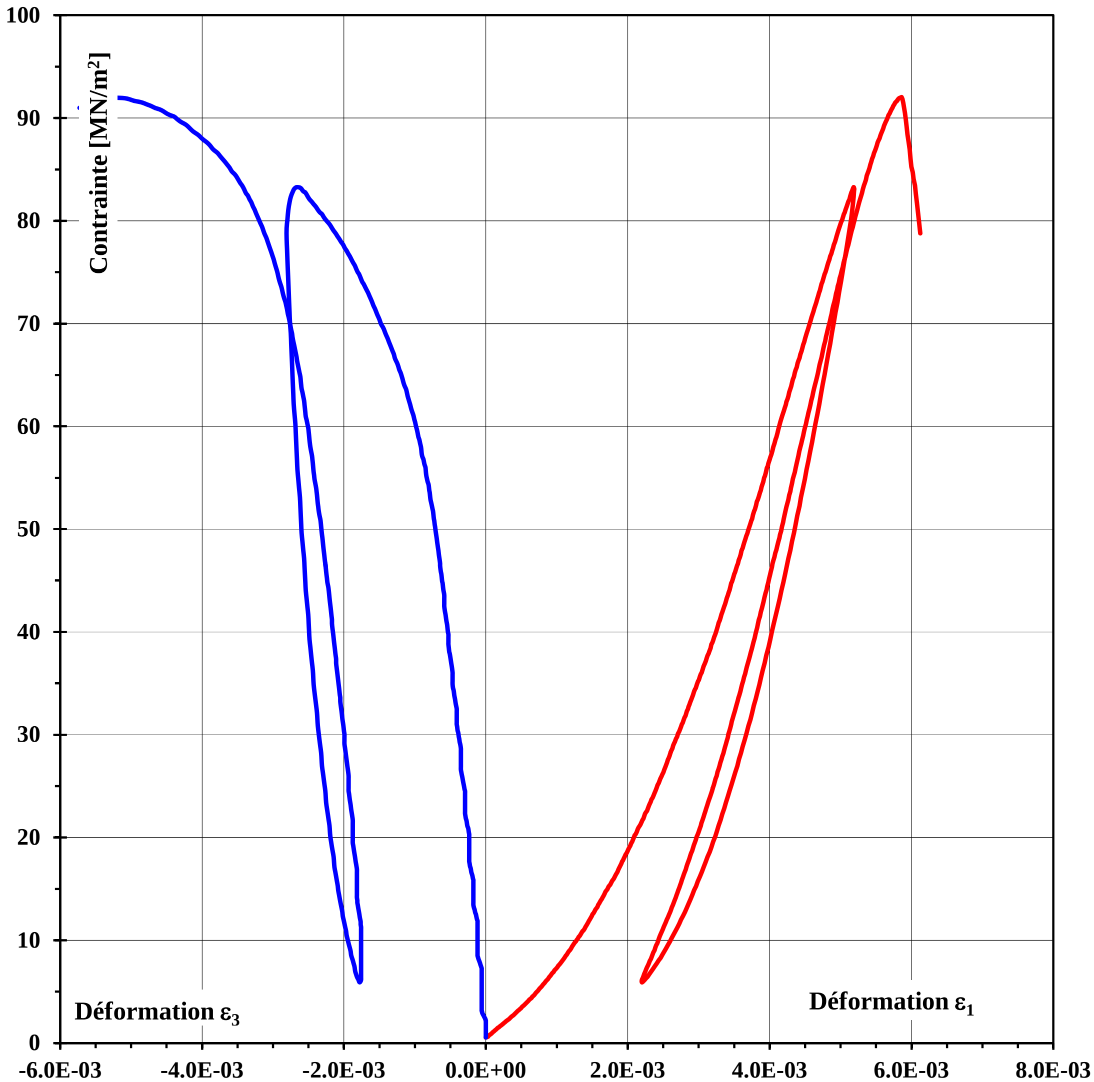
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Khd-RP4	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
116.0	54.3	2.65	-	92.1	22200	27400	0.39



Observations:

LMS-LMR 75 ANS 1935-2010

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

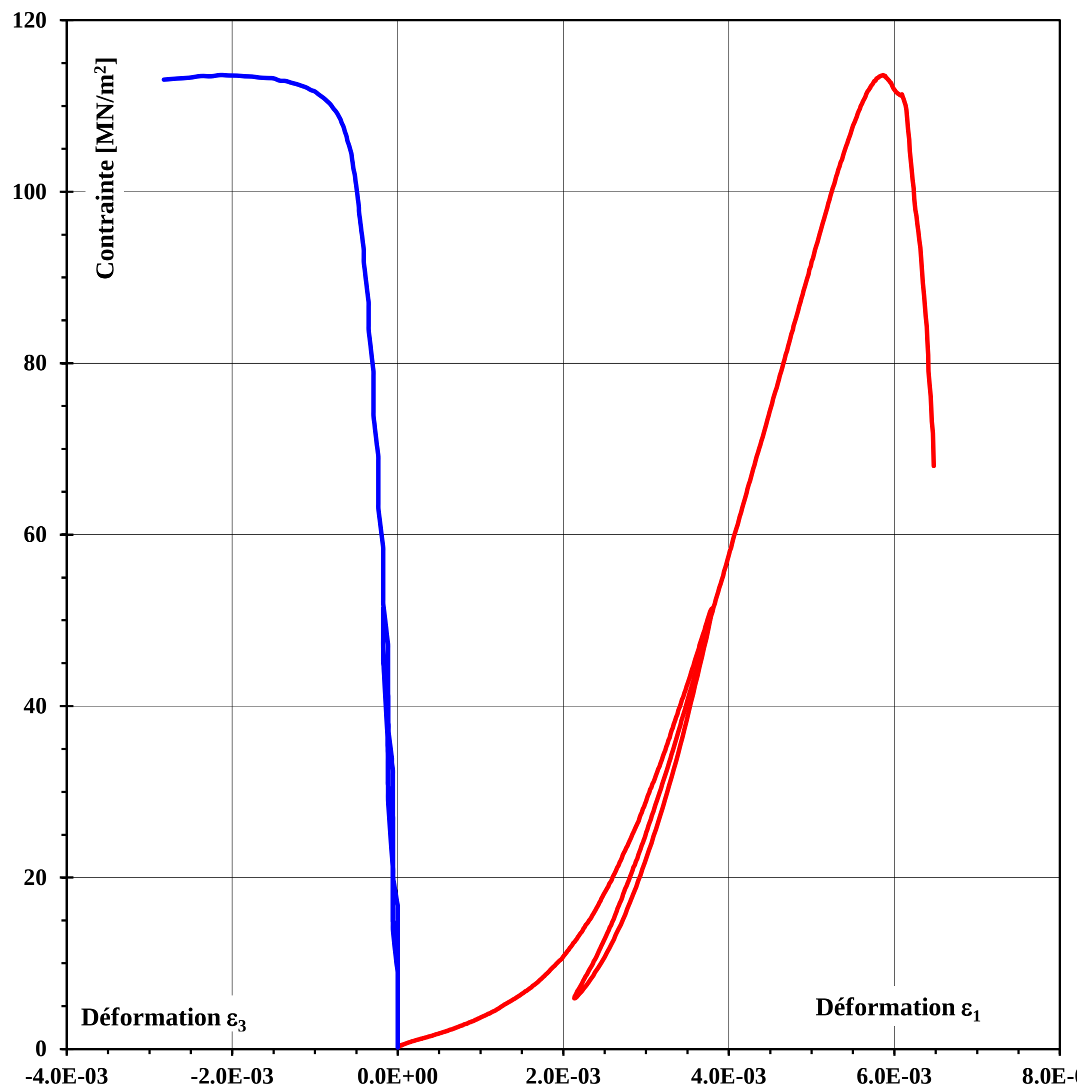
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Khd-ML1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE	[signature]	LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
111.0	54.3	2.66	-	113.6	32400	-	0.16



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

COMPRESSION UNIAXIALE

Exécuté selon la norme SN 670 353 et LMS+R ER.520

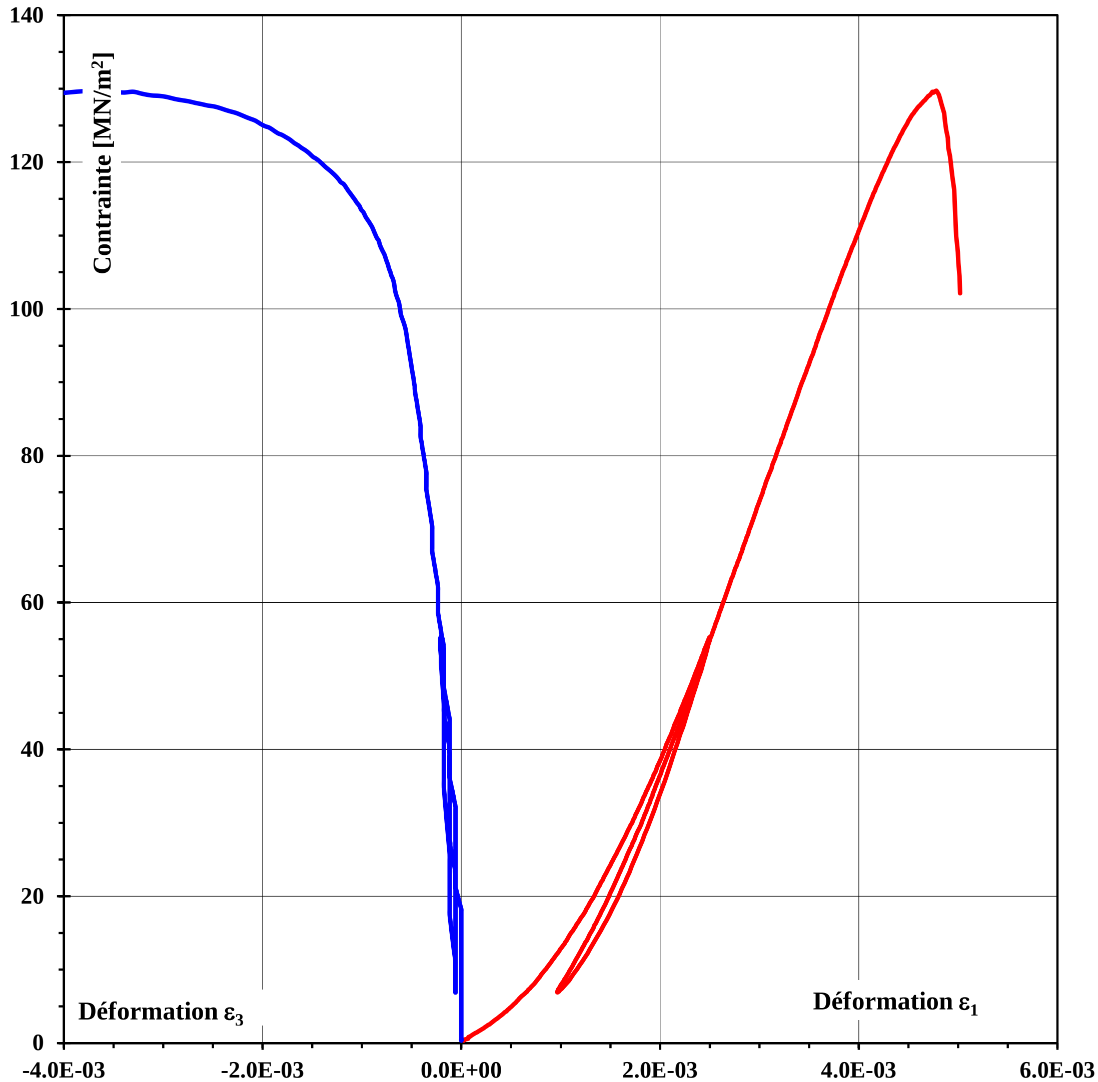
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Khd-ML2	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	26.08.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	σ_c [MN/m^2]	Ep50% [MN/m^2]	$E_{recharge}$ [MN/m^2]	ν
116.5	54.3	2.67	-	129.7	36800	-	0.21



Observations:

Sample R0839-Kec-CS1 before

Sample R0839-Kec-CS1 after

Sample R0839-Kec-CS3 before

Sample R0839-Kec-CS3 after

Sample R0839-Kec-CS4 before

Sample R0839-Kec-CS4 after

Sample R0839-Kgb-NT1 before

Sample R0839-Kgb-NT1 after

Sample R0839-Kgb-NT2 before

Sample R0839-Kgb-NT2 after

Sample R0839-Kgb-NT3 before

Sample R0839-Kgb-NT3 after

Sample R0839-Kt-RA1 before

Sample R0839-Kt-RA1 after

Sample R0839-Kt-RA3 before

Sample R0839-Kt-RA3 after

Sample R0839-Kt-RA4 before

Sample R0839-Kt-RA4 after

Sample R0839-Kd-ZT1 before

Sample R0839-Kd-ZT1 after

Sample R0839-Kd-ZT3 before

Sample R0839-Kd-ZT3 after

Sample R0839-Kd-ZT4 before

Sample R0839-Kd-ZT4 after

Sample R0839-Ks-IC3 before

Sample R0839-Ks-IC3 after

Sample R0839-Ks-IC4 before

Sample R0839-Ks-IC4 after

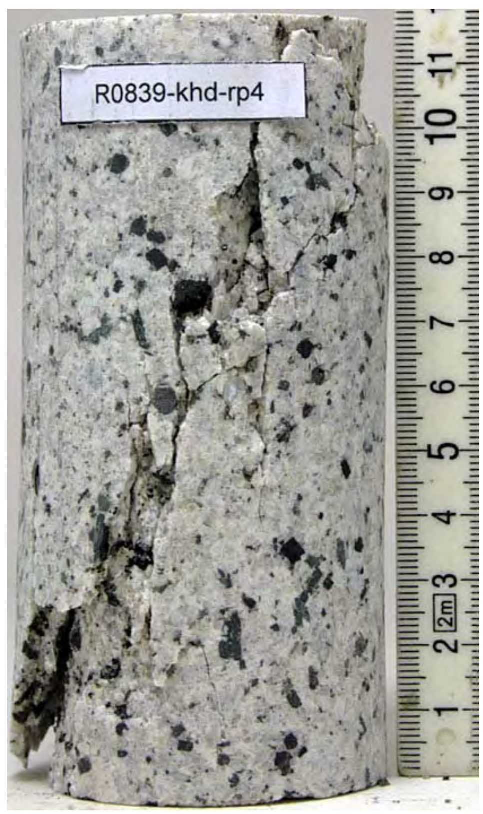
Sample R0839-Ks-IC5 before

Sample R0839-Ks-IC5 after

Sample R0839-Khd-RW1 before

Sample R0839-Khd-RW1 after

Sample R0839-Khd-RP4 before



Sample R0839-Khd-RP4 after

Sample R0839-Khd-ML1 before

Sample R0839-Khd-ML1 after

Sample R0839-Khd-ML2 before

Sample R0839-Khd-ML2 after

Appendix 2. Triaxial Compressive Strength Test Results and Sample Photographs

This appendix contains the stress-strain results and before and after photographs for each of the 12 triaxial compressive strength tests performed on the Yosemite Valley rock samples. Because the testing was performed at the French-speaking Laboratoires de Mecanique des Sols et des Roches (Soil and Rock Mechanics Laboratory) at the École Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology Lausanne, EPFL) in Lausanne, Switzerland, the data sheets containing the results are in French. A key to pertinent information contained on these forms is included here. Note that “Ep50%” is equivalent to E_{50} as used in the main text of this report.

SOIL AND ROCK MECHANICS LABORATORY

TRIAXIAL TEST

Executed according to the standard ASTM D 2664-86 and LMS+R ER.620

Sample Number		Title of the Study	Client		
			Name		Address
R0839-Kec-CS1		ESSAIS UNIL-USGS	UNIL		LAUSANNE
Borehole Number	Depth [m]	Sample description	Sample collected by	Date received	Date tested
Kec	-	EL CAPITAN GRANITE	Client	08.07.14	02.09.14

Sample storage method	Sample preparation method	Engineer in charge		Operator
		Name	Signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Height [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
117.3	54.3	2.67	-	30800	-	154.4

French	English
Contrainte [MN/m^2]	Stress [MPa]
Deformation, ε_1, ε_3	Strain, ε_1, ε_3
Val. pic	Peak value
Val. res.	Residual value
Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l’éprouvette testée. En outre, il fait partie d’une série d’essais, voir page “Rapport d’essais.”	These test results cannot be perfectly reproduced and only apply to the sample tested. In addition, the results are part of a series of tests—see the test report page.

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

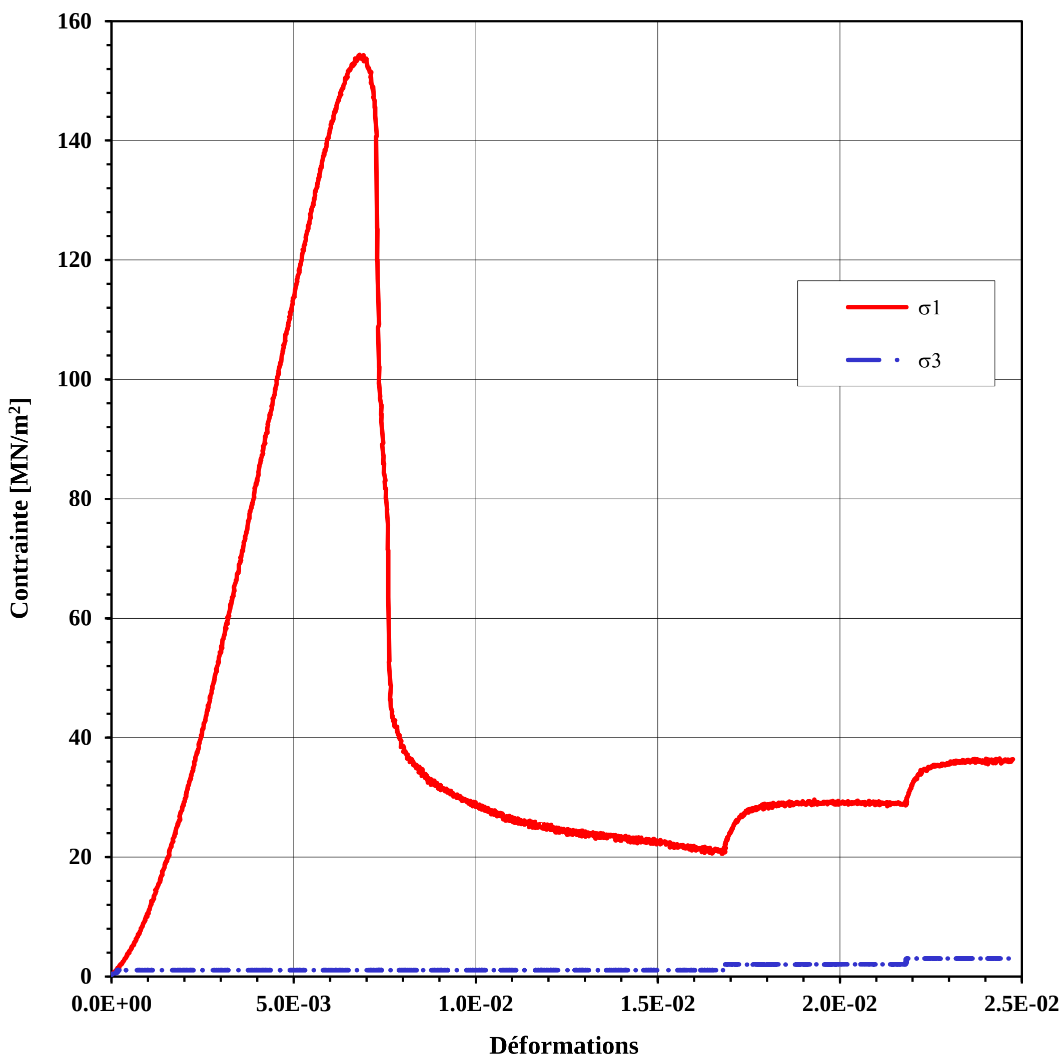
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Kec-CS1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
117.3	54.3	2.67	-	30800	-	154.4



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

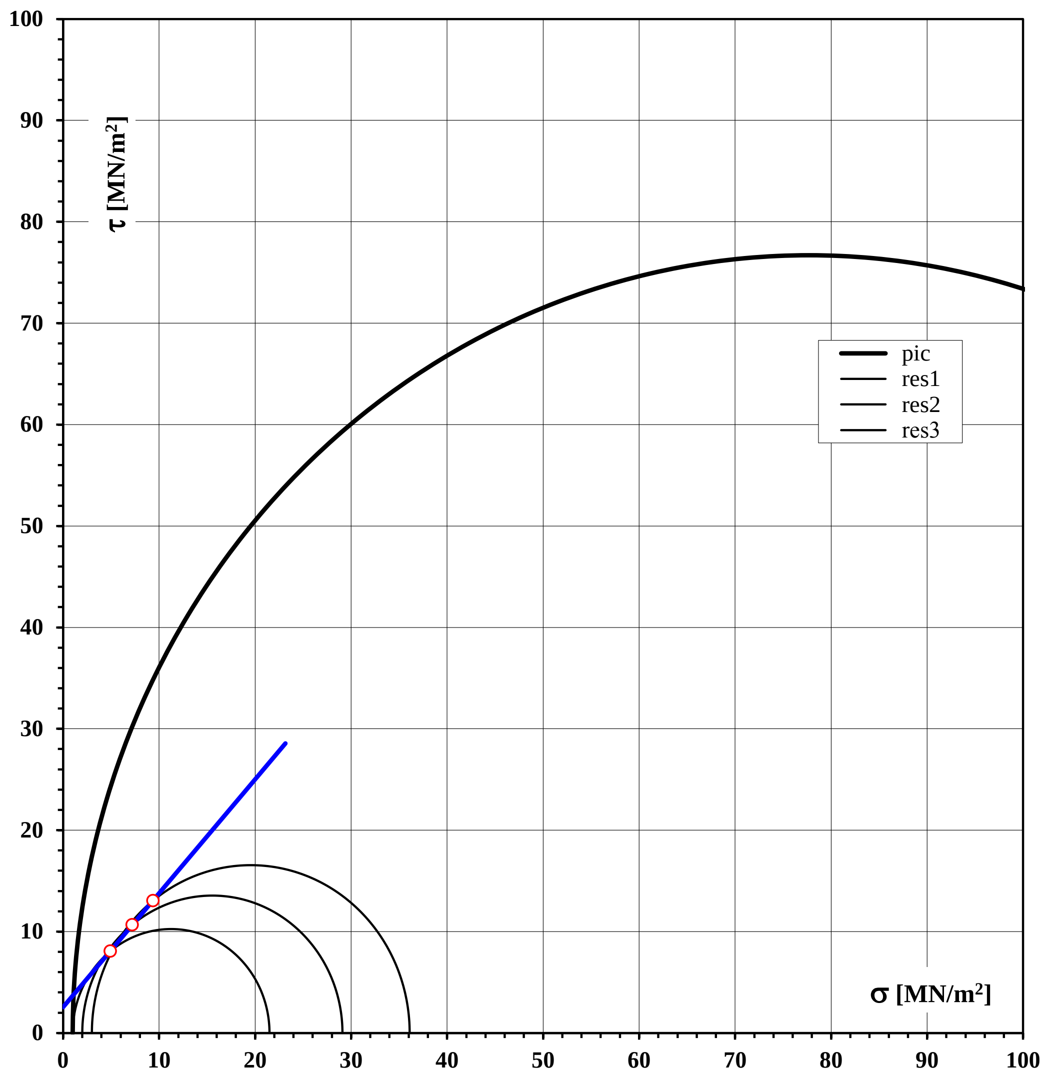
No éprouvette		Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kec-CS1		ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

val. pic	σ_3	σ_1
MN/m2	1.0	154.4

val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	1.0	21.5	2.0	29.1	3.0	36.1	48.0	2.5



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

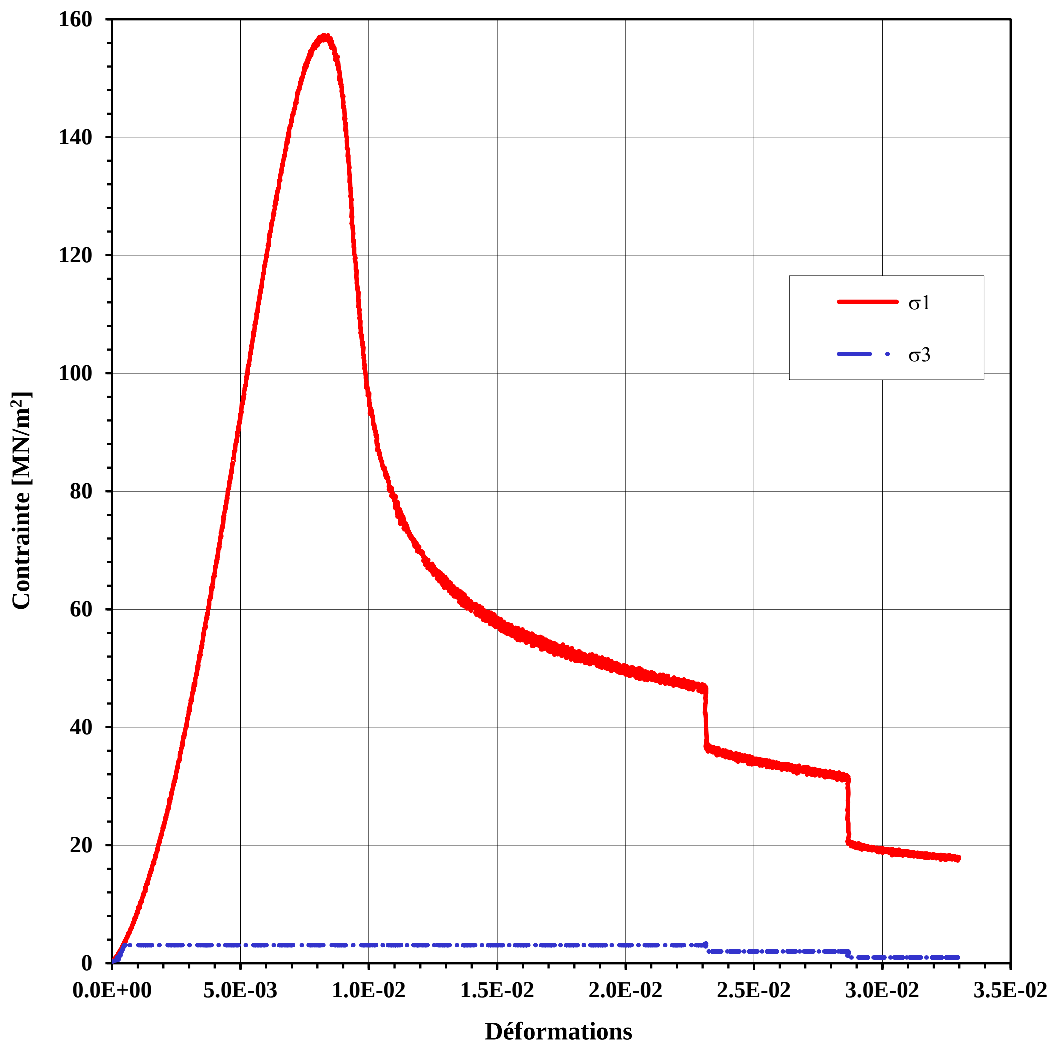
ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette		Titre de l'étude		Commettant nom		adresse
R0839-Kec-CS3		ESSAIS UNIL-USGS		UNIL		LAUSANNE
No sond.	**Prof. [m]**	**Nature échantillon**		**Echantillon prélevé par**	**Date réception**	**Date essai**
Kec	-	EL CAPITAN GRANITE		COMMETTANT	08.07.14	02.09.14
Mode conservation		**Mode préparation éprouvette**		**Ingénieur responsable nom**	**signature**	**Opérat.**
NATUREL		SCIE, RECTIFIE		F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
116.4	54.3	2.69	-	24600	-	157.3



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

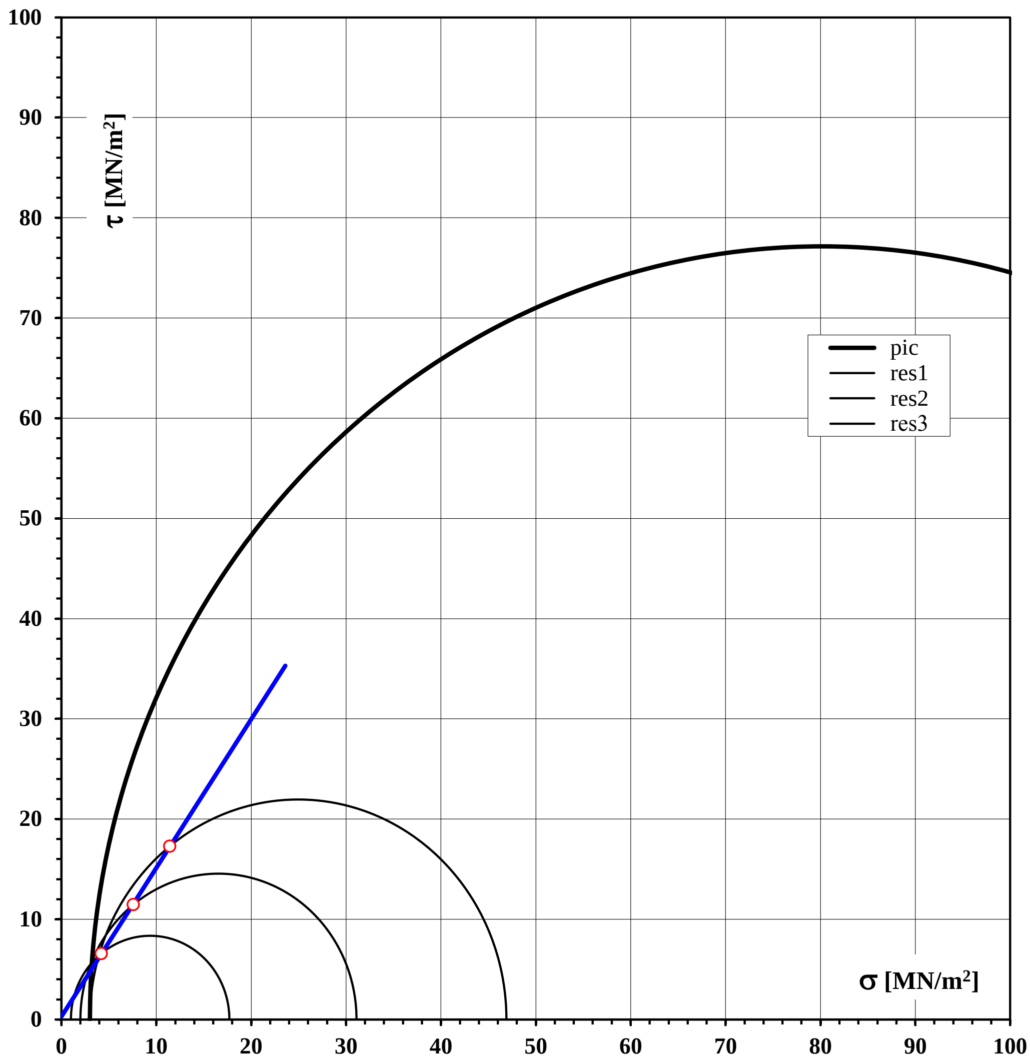
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Kec-CS3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1	val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	3.0	157.3	MN/m2	3.0	46.9	2.0	31.1	1.0	17.7	56.0	0.3



Observations:

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

ESSAI TRIAXIAL

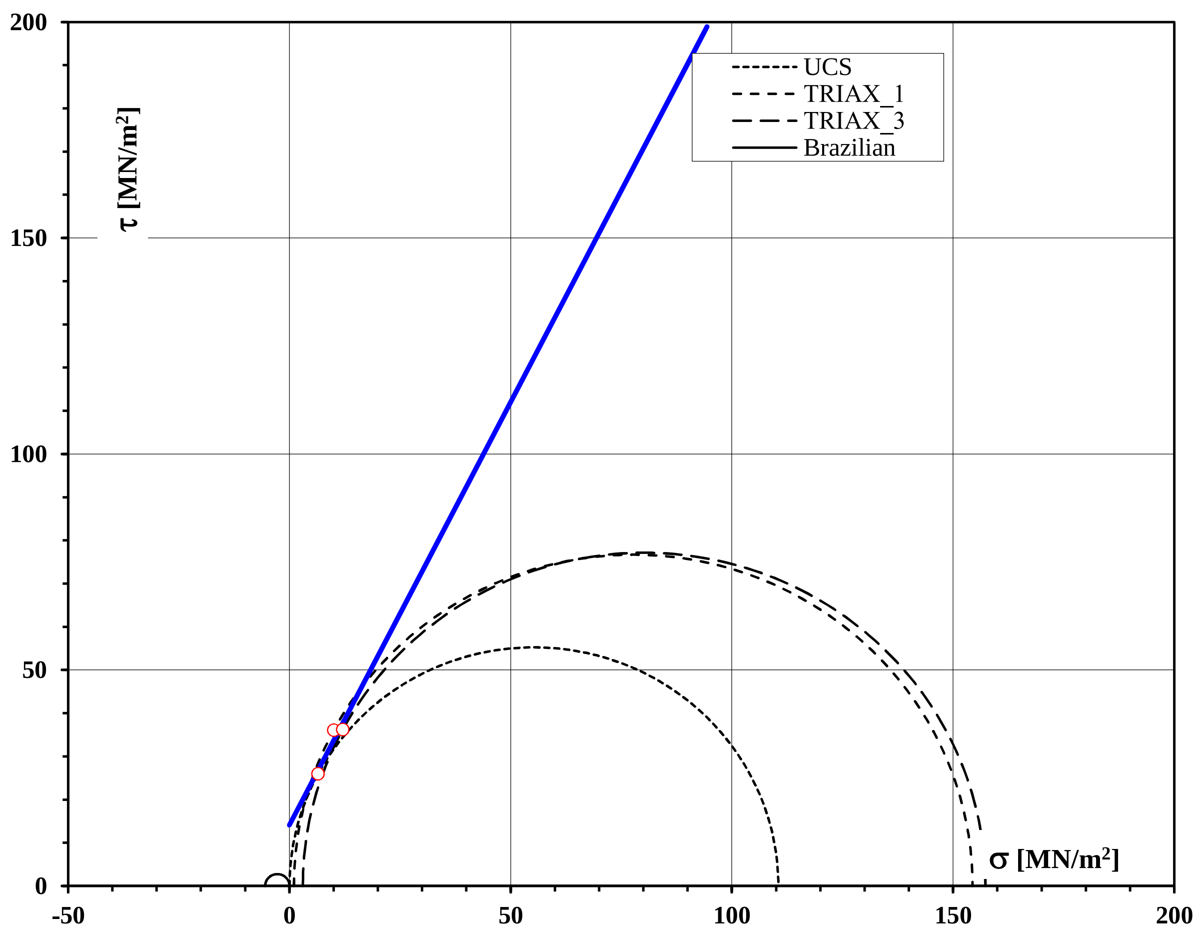
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
CS1, CS3	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
El Capitan Granite (Kec)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone		BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	110.5	1.0	154.4	3.0	157.3	-5.5	0.0	63.0	14.1



Observations:

LEMR
LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

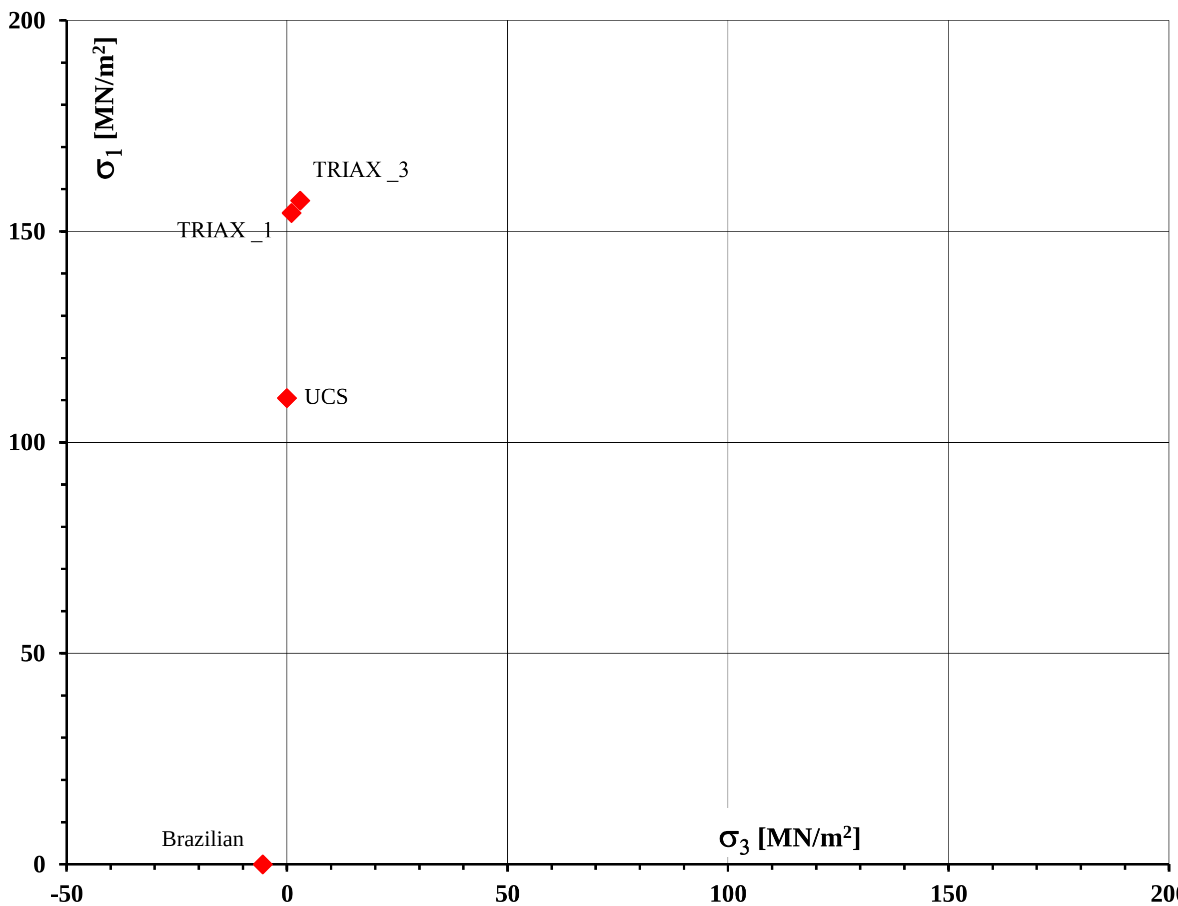
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
CS1, CS3	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
El Capitan Granite (Kec)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone		BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	110.5	1.0	154.4	3.0	157.3	-5.5	0.0	60.0	16.6



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

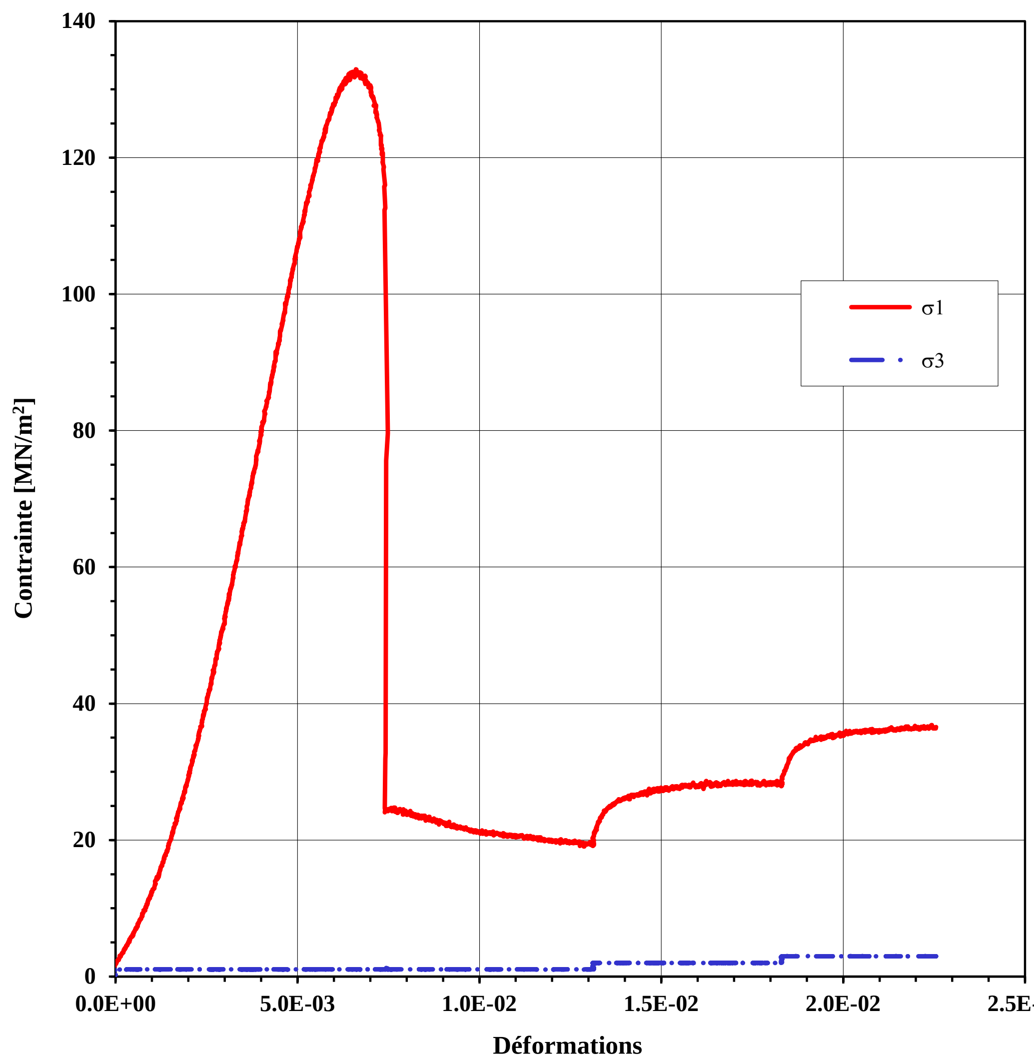
ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette		Titre de l'étude	Commettant		
			nom		adresse
R0839-Kgb-NT1		ESSAIS UNIL-USGS	UNIL		LAUSANNE
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	09.09.14
Mode conservation		Mode préparation éprouvette	Ingénieur responsable		Opérat.
			nom	signature	
NATUREL		SCIE, RECTIFIE	F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
117.2	54.4	2.77	-	25500	-	132.9



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée
En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

LMS-LMR 75 ANS 1935-2010

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

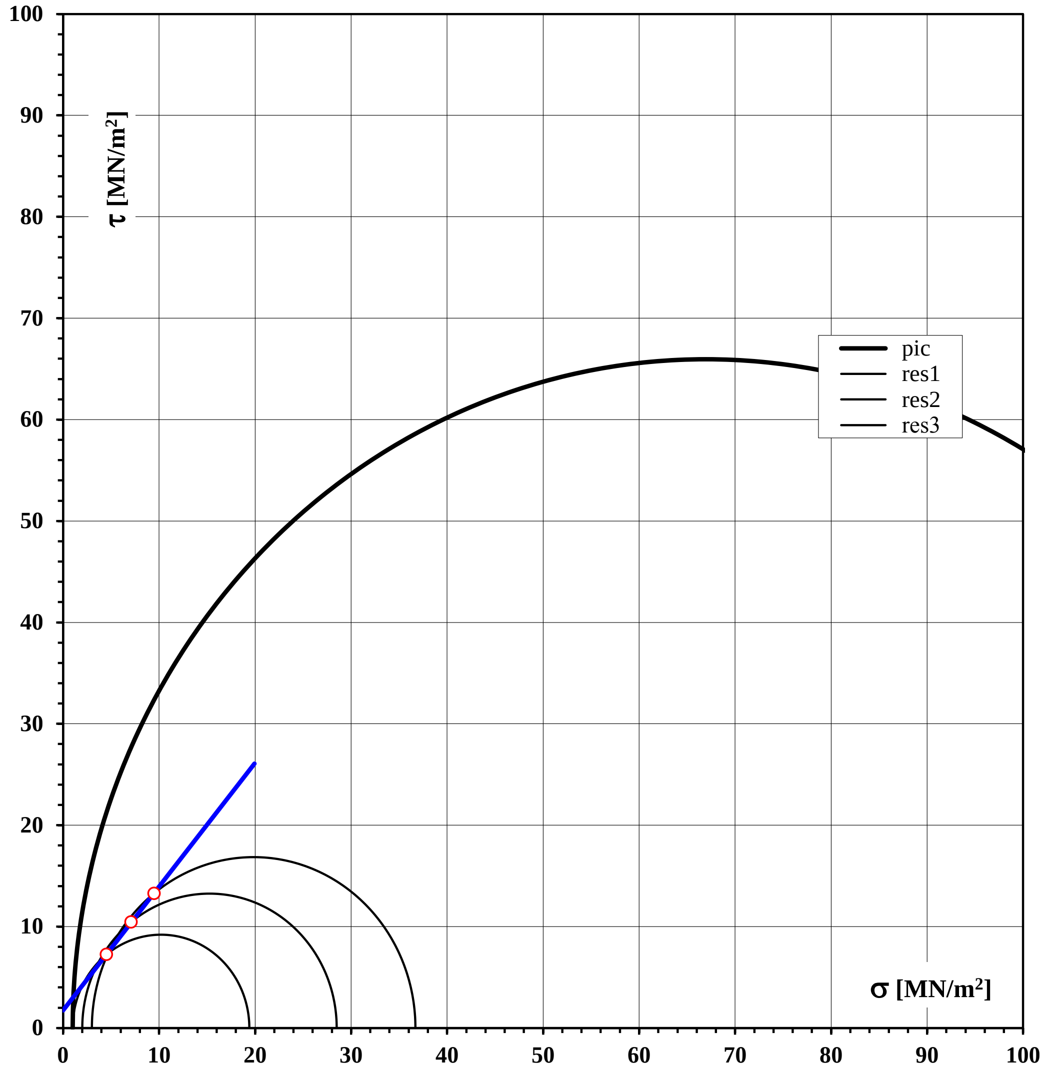
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette		Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kgb-NT1		ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1	val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	1.0	132.9	MN/m2	1.0	19.4	2.0	28.5	3.0	36.7	51.0	1.7



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

LMS-LMR 75 ANS 1935-2010

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

ESSAI TRIAXIAL

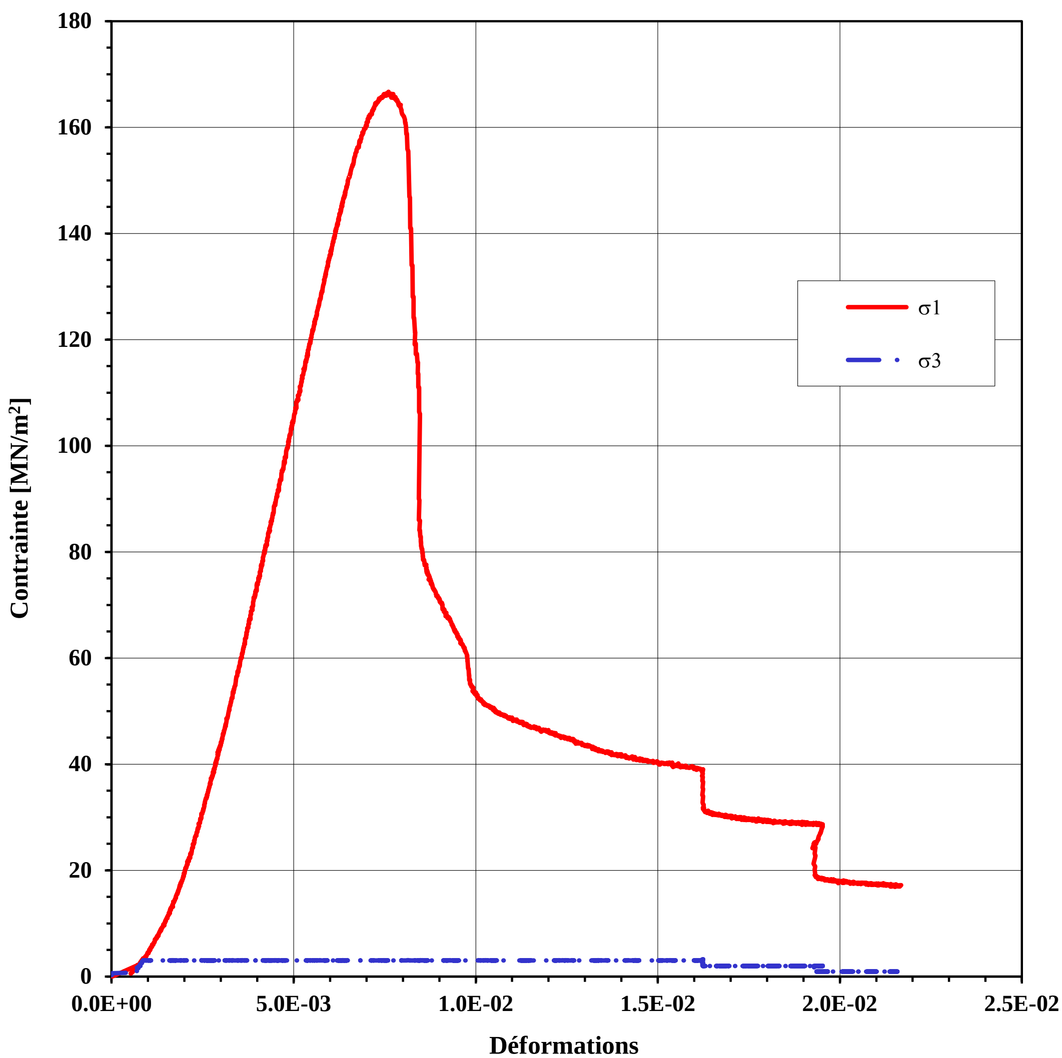
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kgb-NT3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
117.5	54.4	2.72	-	29500	-	166.7



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

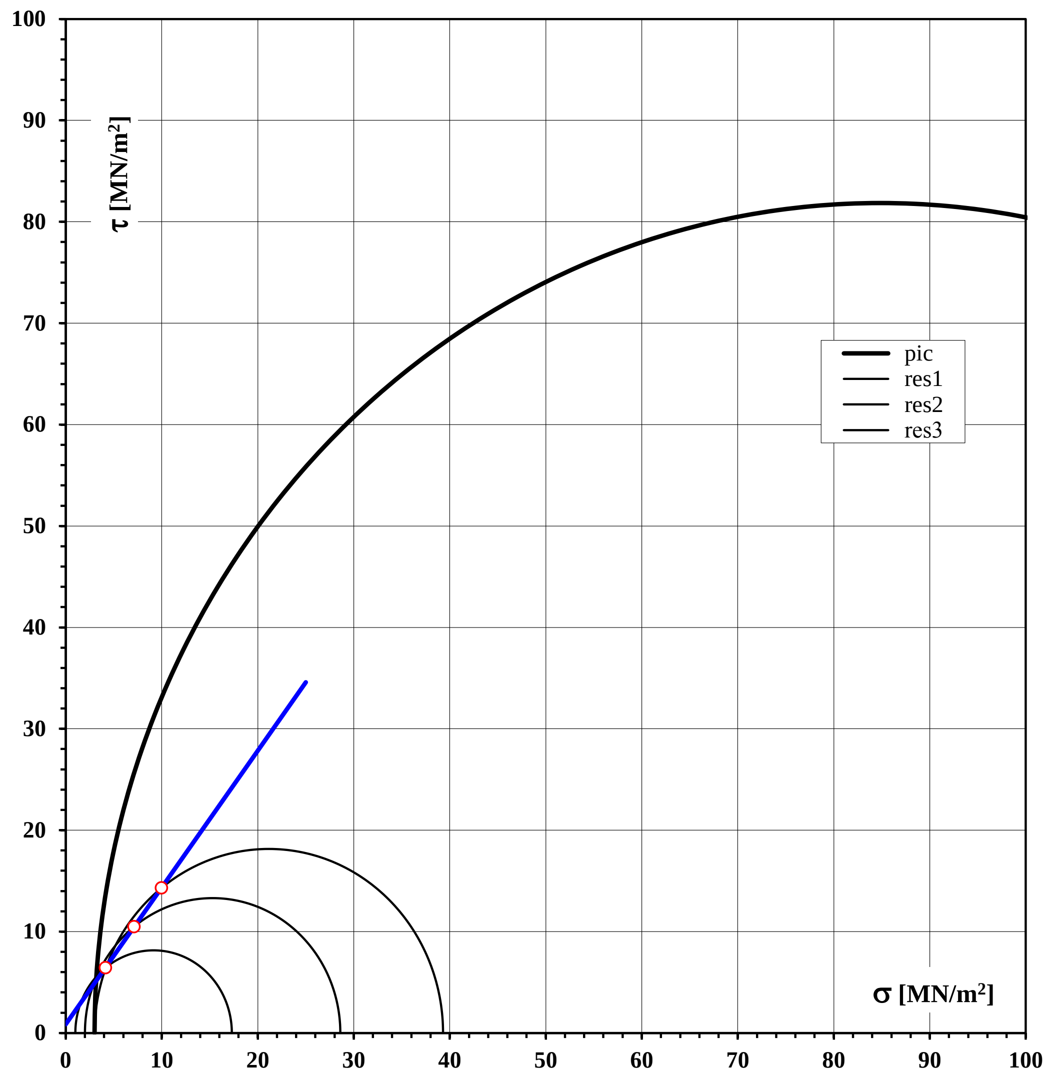
No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kgb-NT3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1
MN/m2	3.0	166.7

val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	3.0	39.3	2.0	28.6	1.0	17.3	53.0	0.9



Observations:

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R0839-Kgb-NT3_Triax.xlsx ER.620 01/99

LEMR LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

ESSAI TRIAXIAL

EPFL

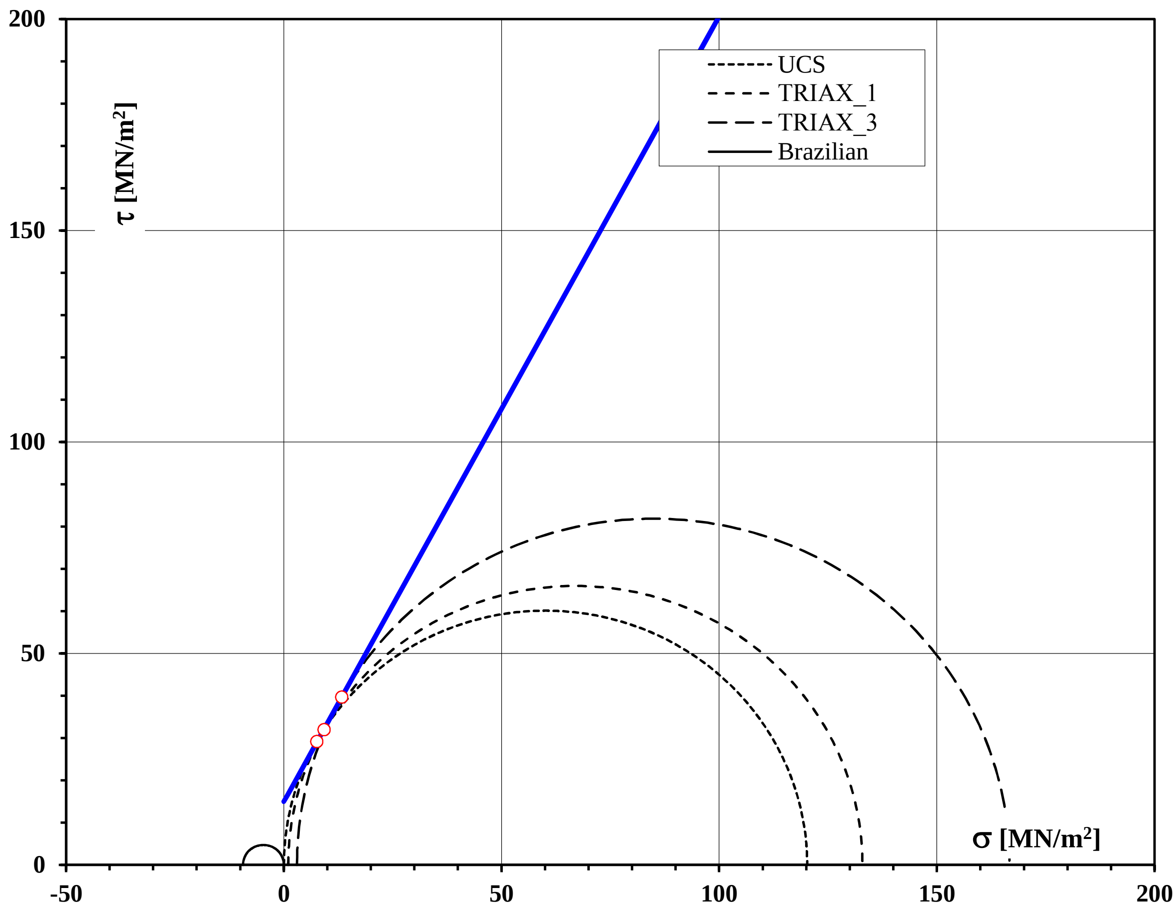
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant: nom	Commettant: adresse
NT1, NT3	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
tonalite of the Gray Bands (Kgb)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable: nom	Ingénieur responsable: signature	Opérateur
NATUREL	SCIE, RECTIFIE	F. Sandrone	[signature]	BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	120.2	1.0	132.9	3.0	166.7	-9.4	0.0	62.0	15.0



Observations:

LEMR
LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

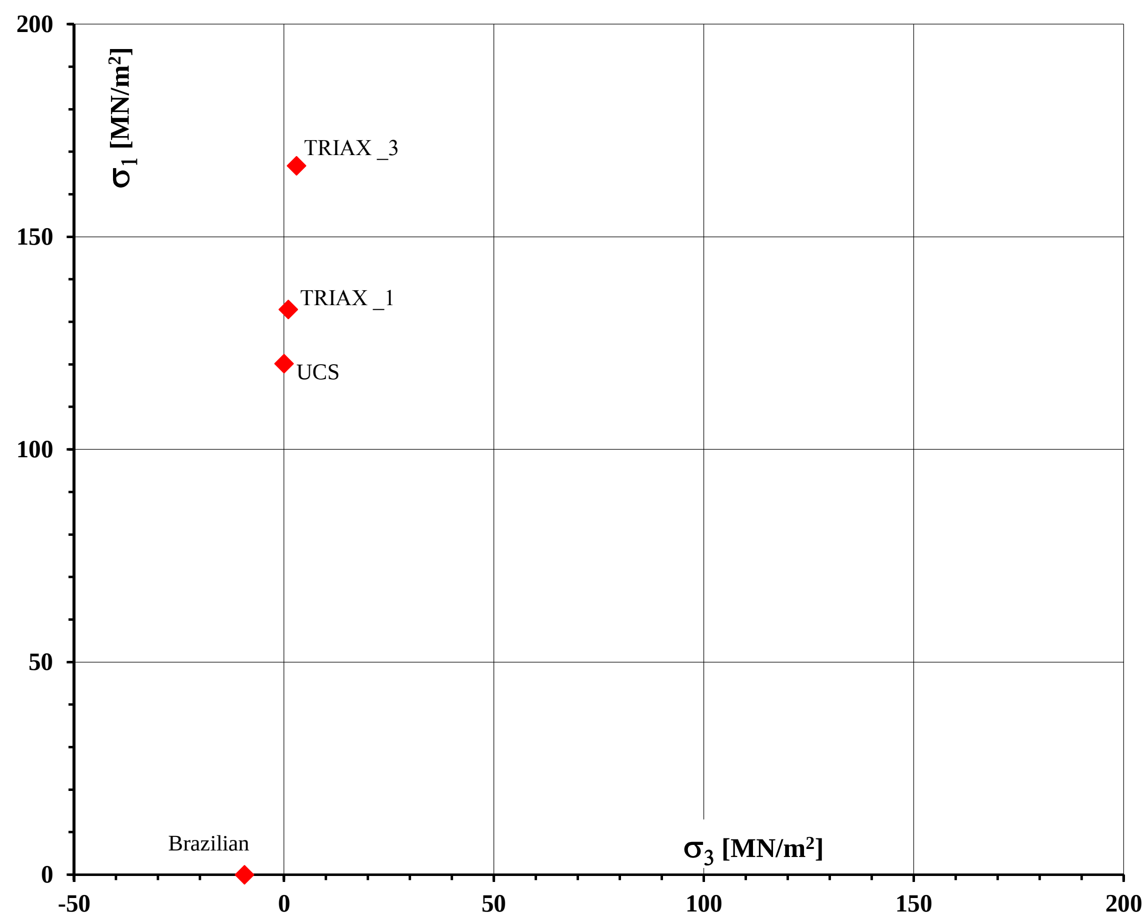
EPFL

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
NT1, NT3	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
tonalite of the Gray Bands (Kgb)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone		BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	120.2	1.0	132.9	3.0	166.7	-9.4	0.0	62.0	15.0



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

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ER.331 03/16

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

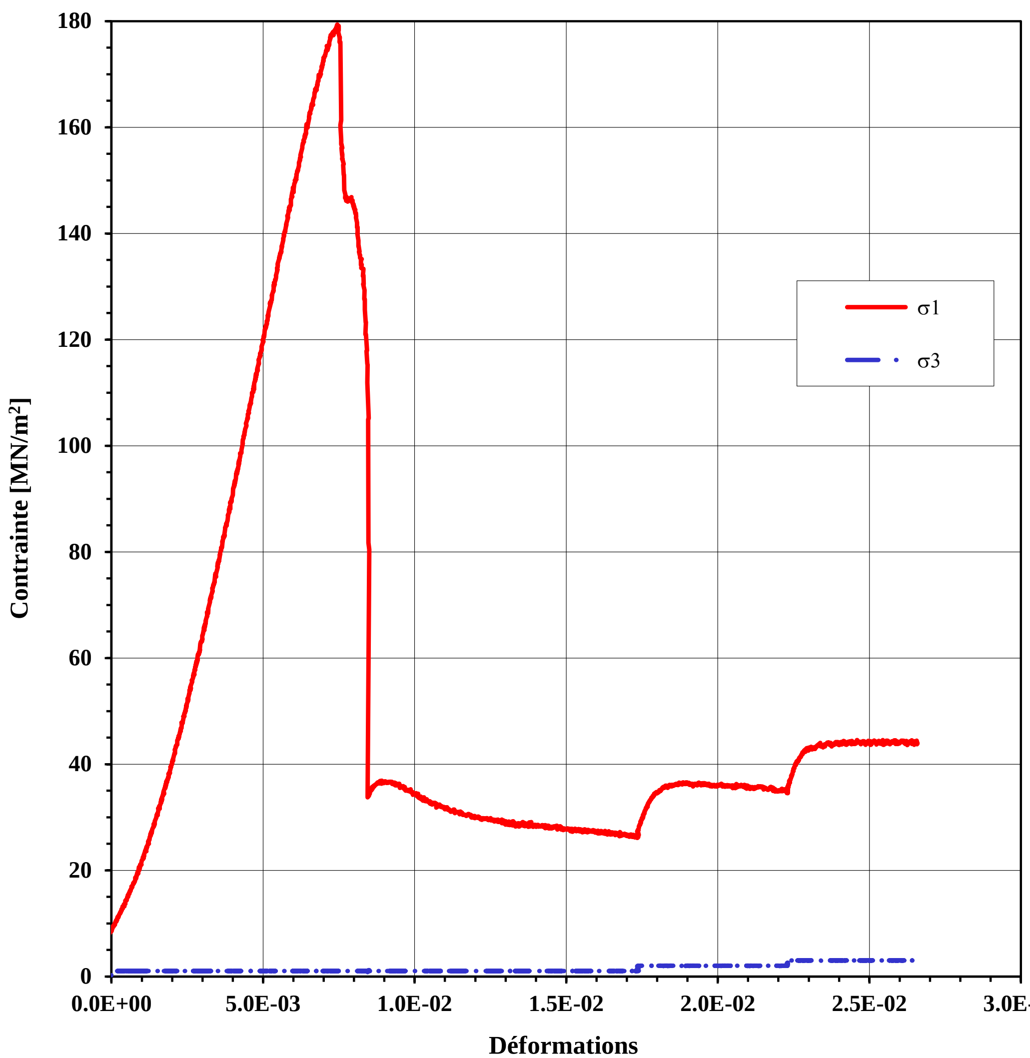
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Kt-RA1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE	[signature]	BF

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
116.5	54.4	2.60	-	26500	-	179.4



Observations:

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En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

LMS-LMR 75 ANS 1935-2010

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

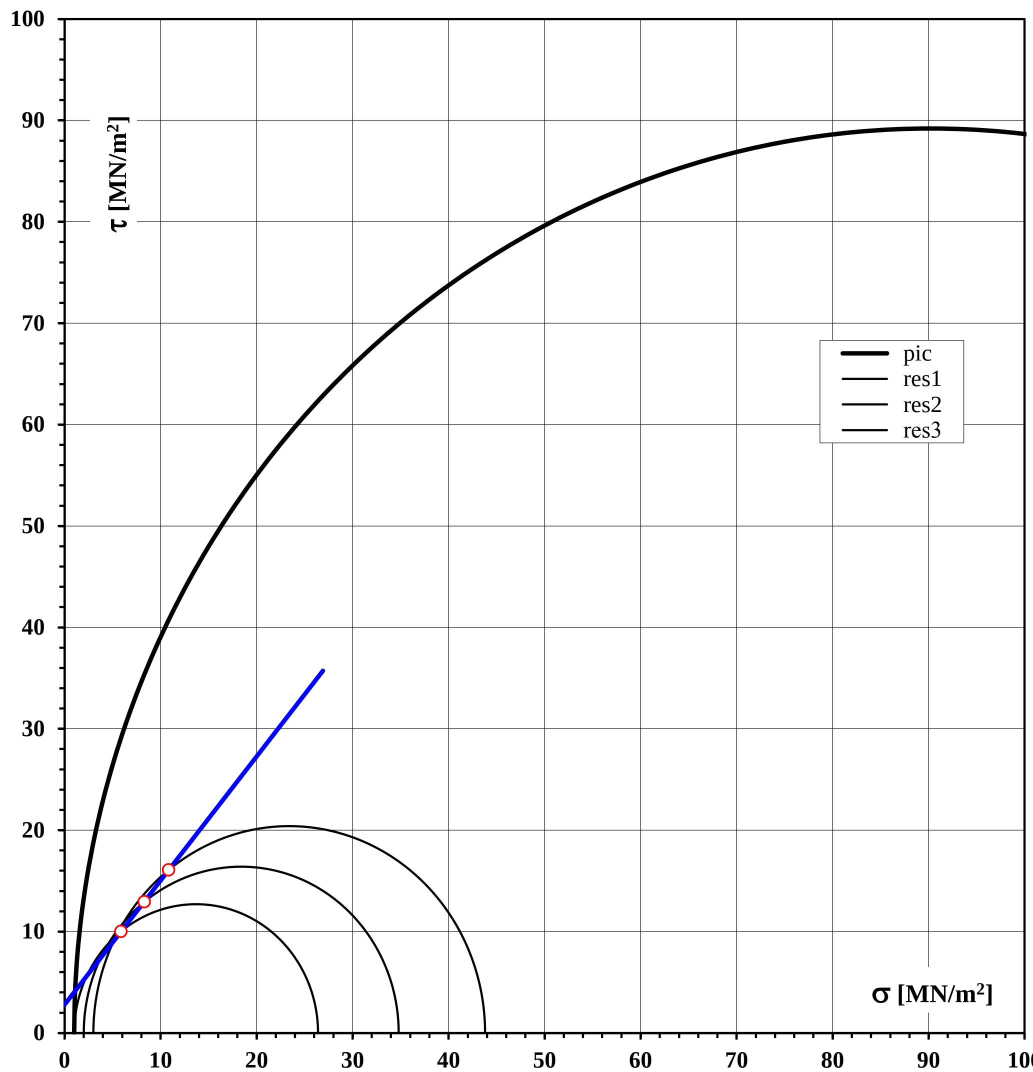
No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kt-RA1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1
MN/m2	1.0	179.4

val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	1.0	26.4	2.0	34.8	3.0	43.8	51.0	2.8



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

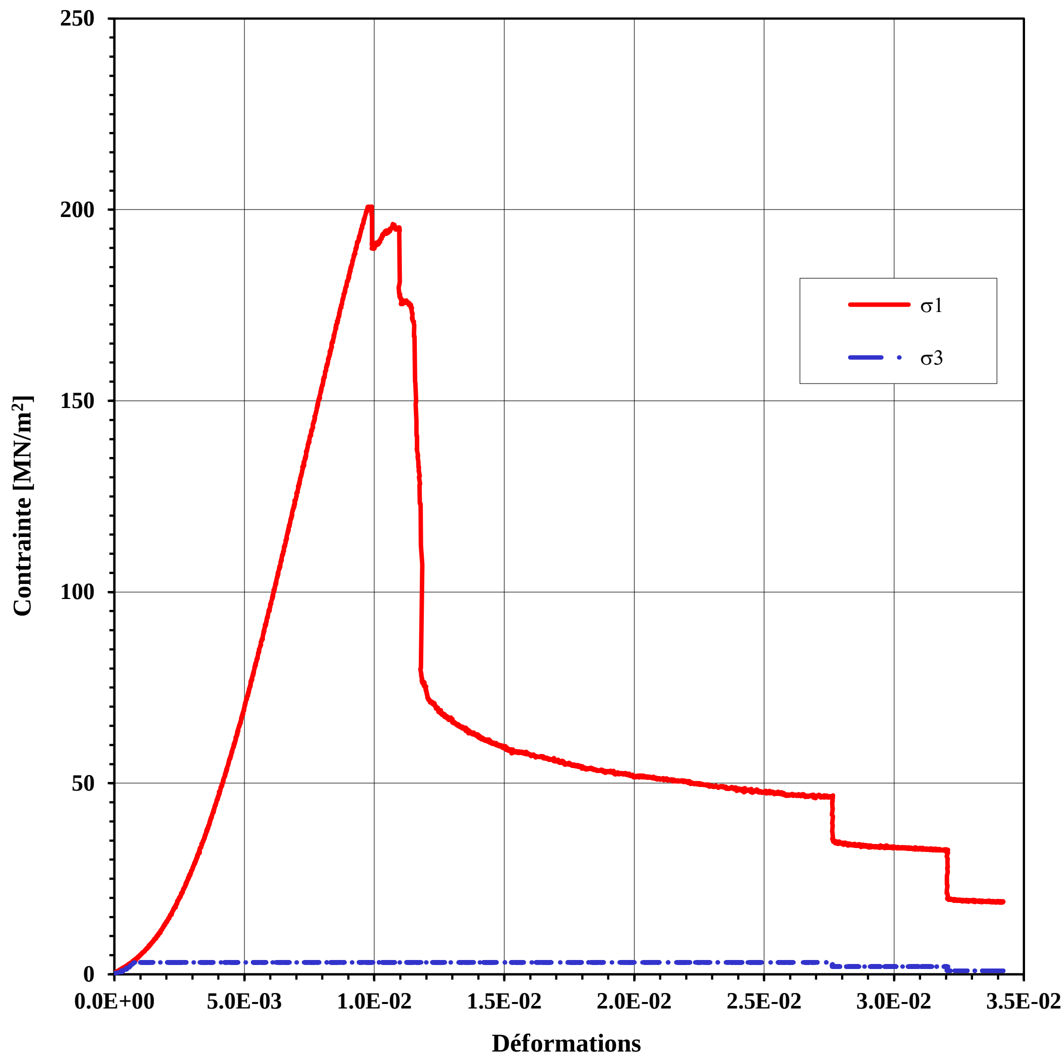
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kt-RA4	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	05.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
115.8	54.4	2.60	-	24400	-	200.8



Observations:

LMS-LMR 75 ANS 1935-2010

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

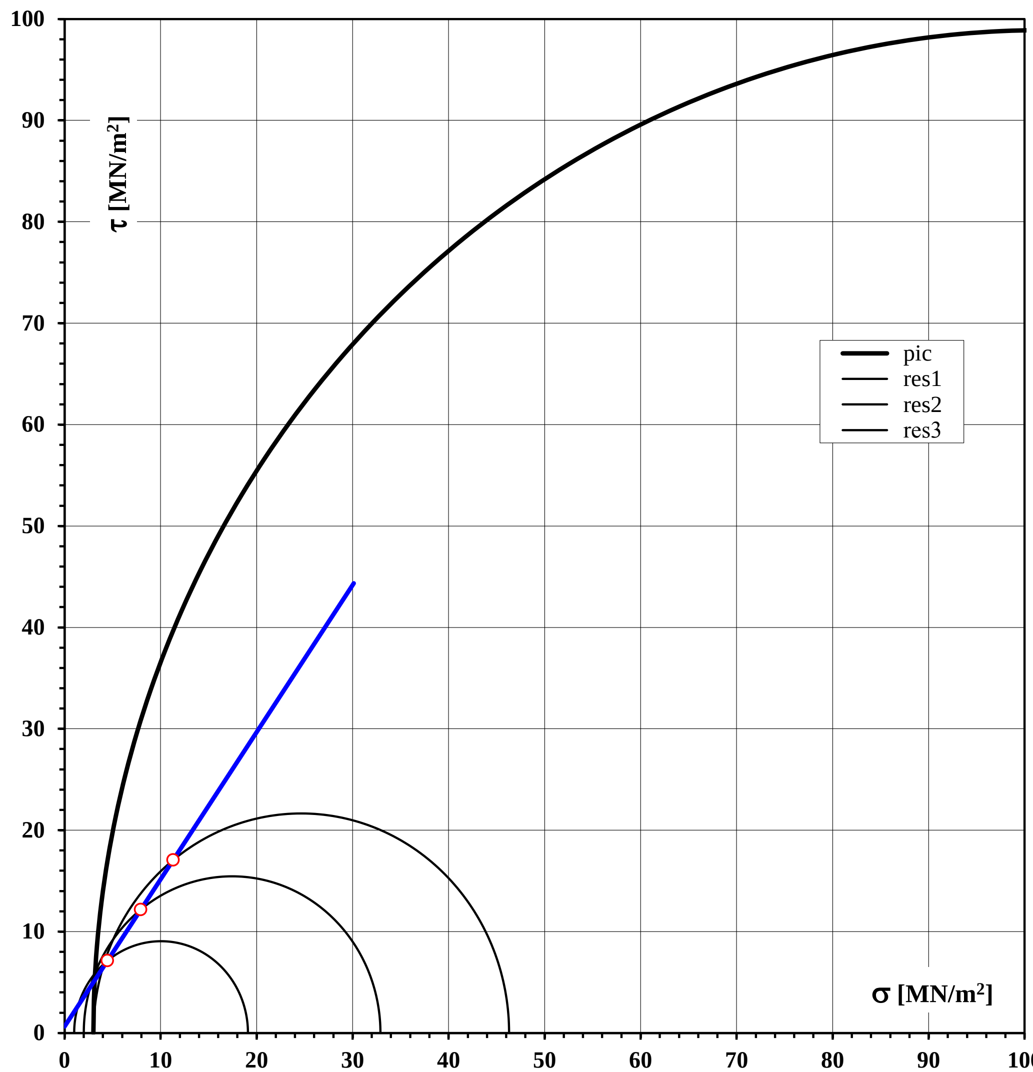
No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kt-RA4	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	05.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1
MN/m2	3.0	200.8

val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	3.0	46.3	2.0	32.9	1.0	19.1	55.0	0.6



Observations:

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LEMR LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

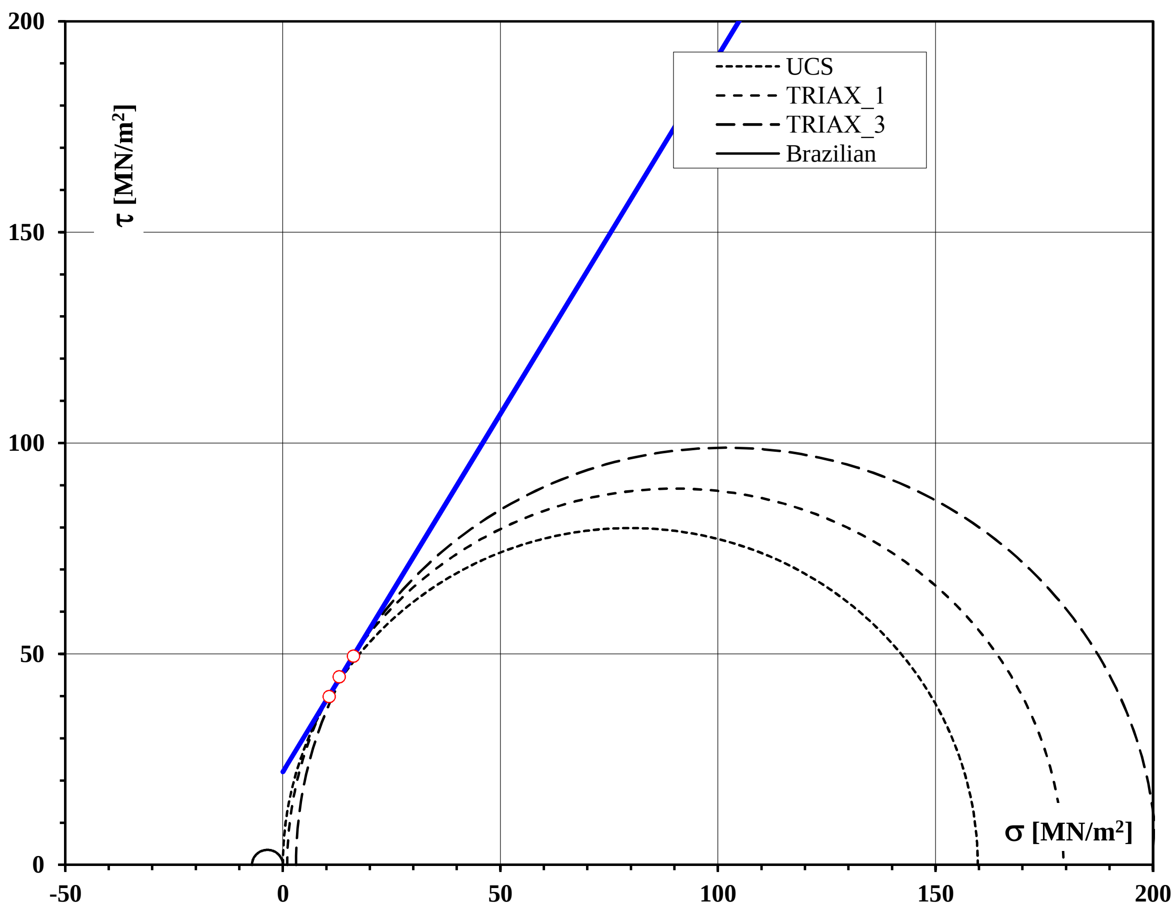
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
RA1, RA4	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Taft Granite (Kt)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone	[signature]	BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	159.7	1.0	179.4	3.0	200.8	-7.1	0.0	59.0	22.1



Observations:

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LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

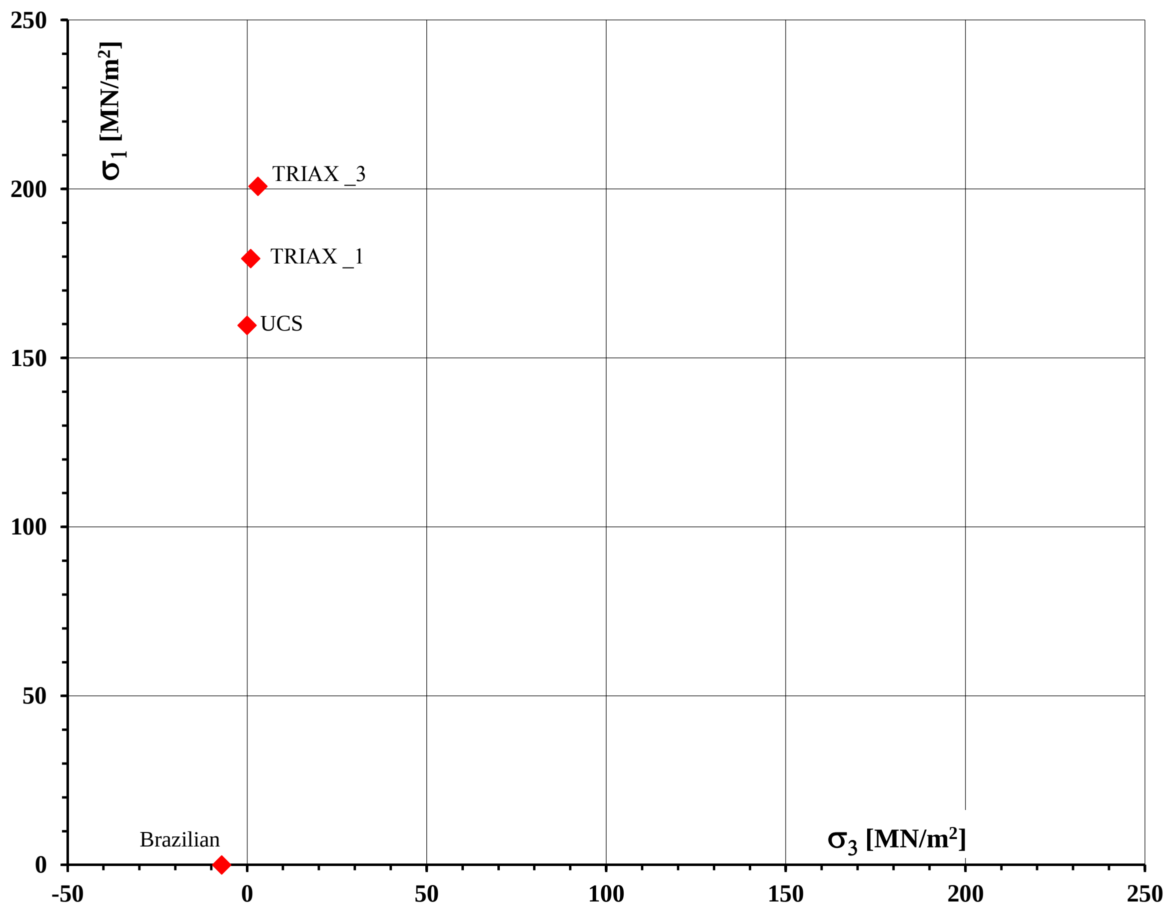
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
RA1, RA4	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Taft Granite (Kt)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone		BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	159.7	1.0	179.4	3.0	200.8	-7.1	0.0	59.0	22.3



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

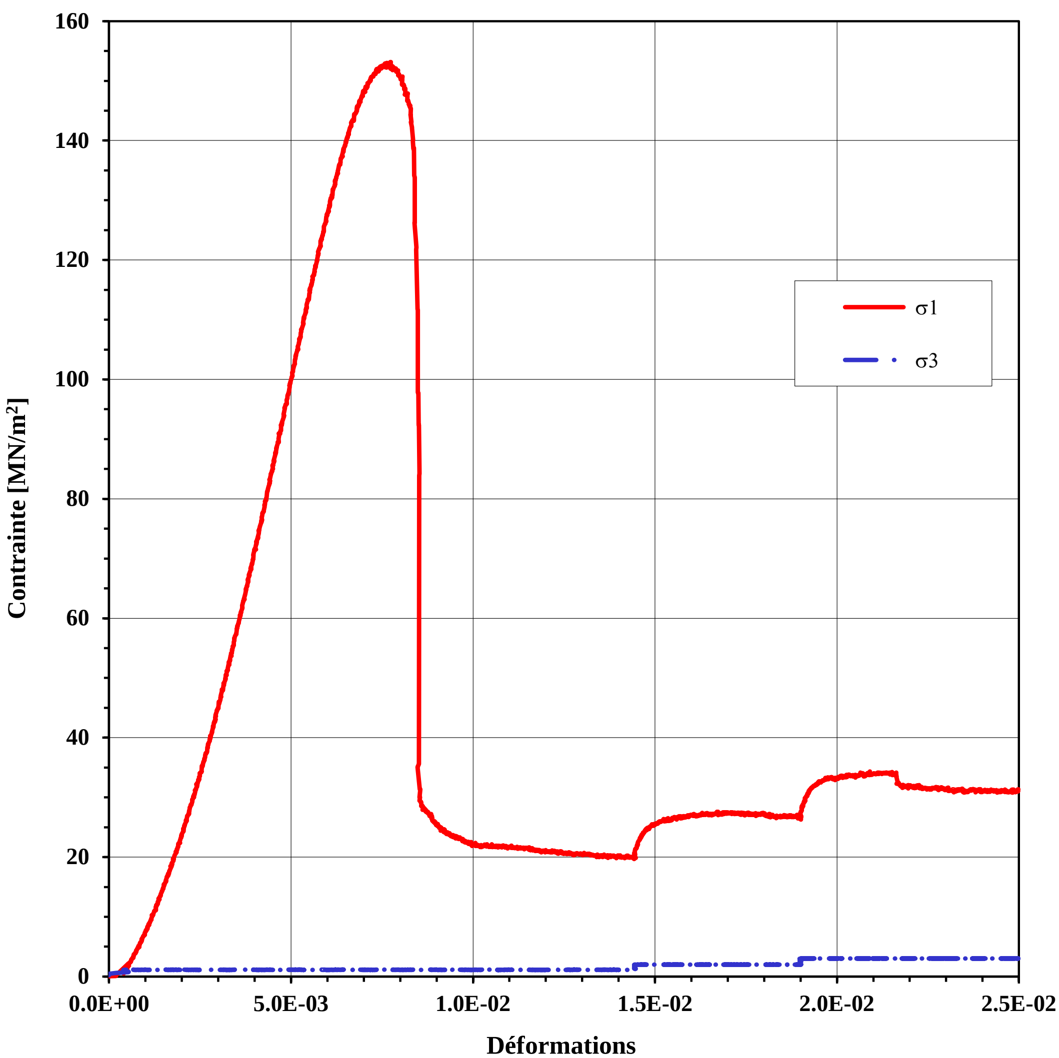
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Kd-ZT1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	05.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
116.8	54.3	2.80	-	26700	-	153.1



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

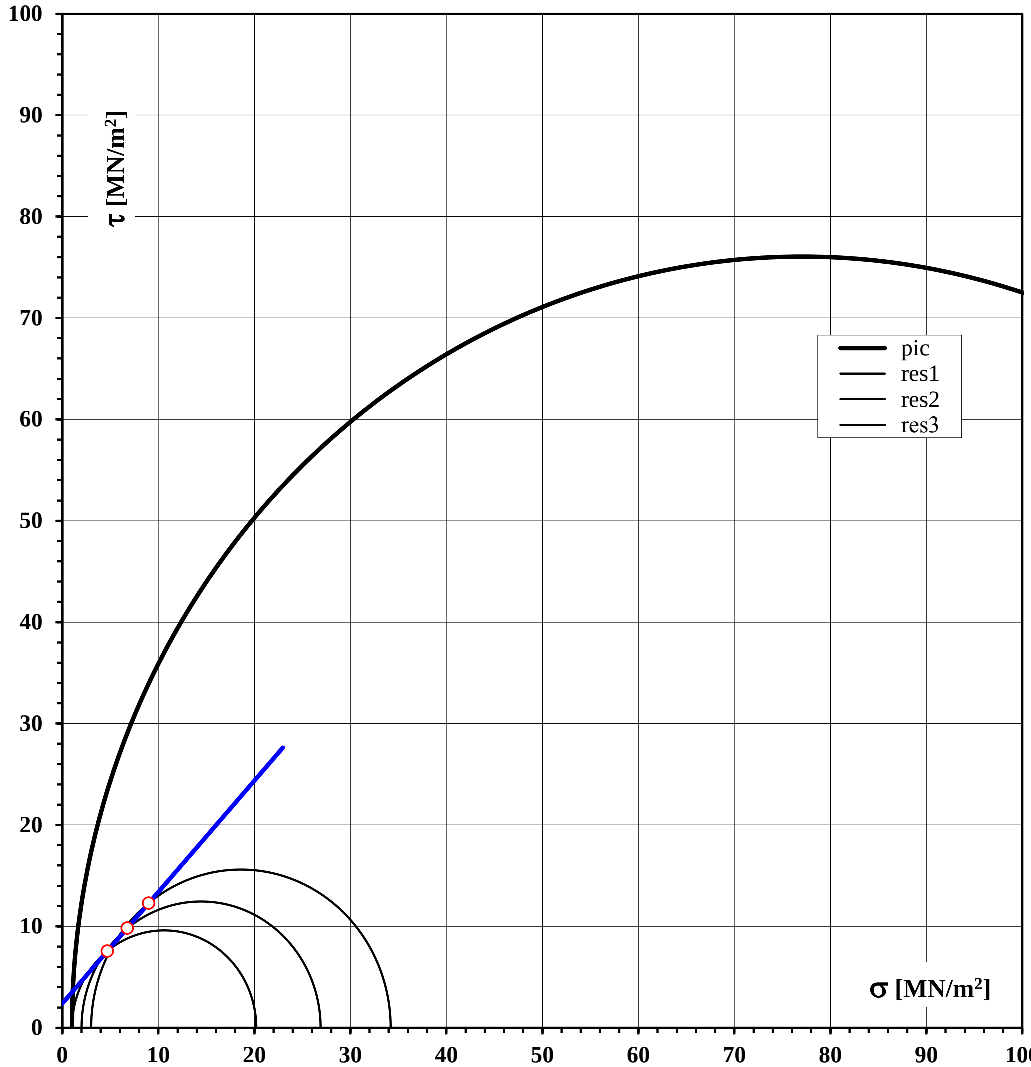
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kd-ZT1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	05.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1	val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	1.0	153.1	MN/m2	1.0	20.2	2.0	26.9	3.0	34.2	48.0	2.4



Observations:

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En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

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R0839-Kd-ZT1_Triax.xlsx

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

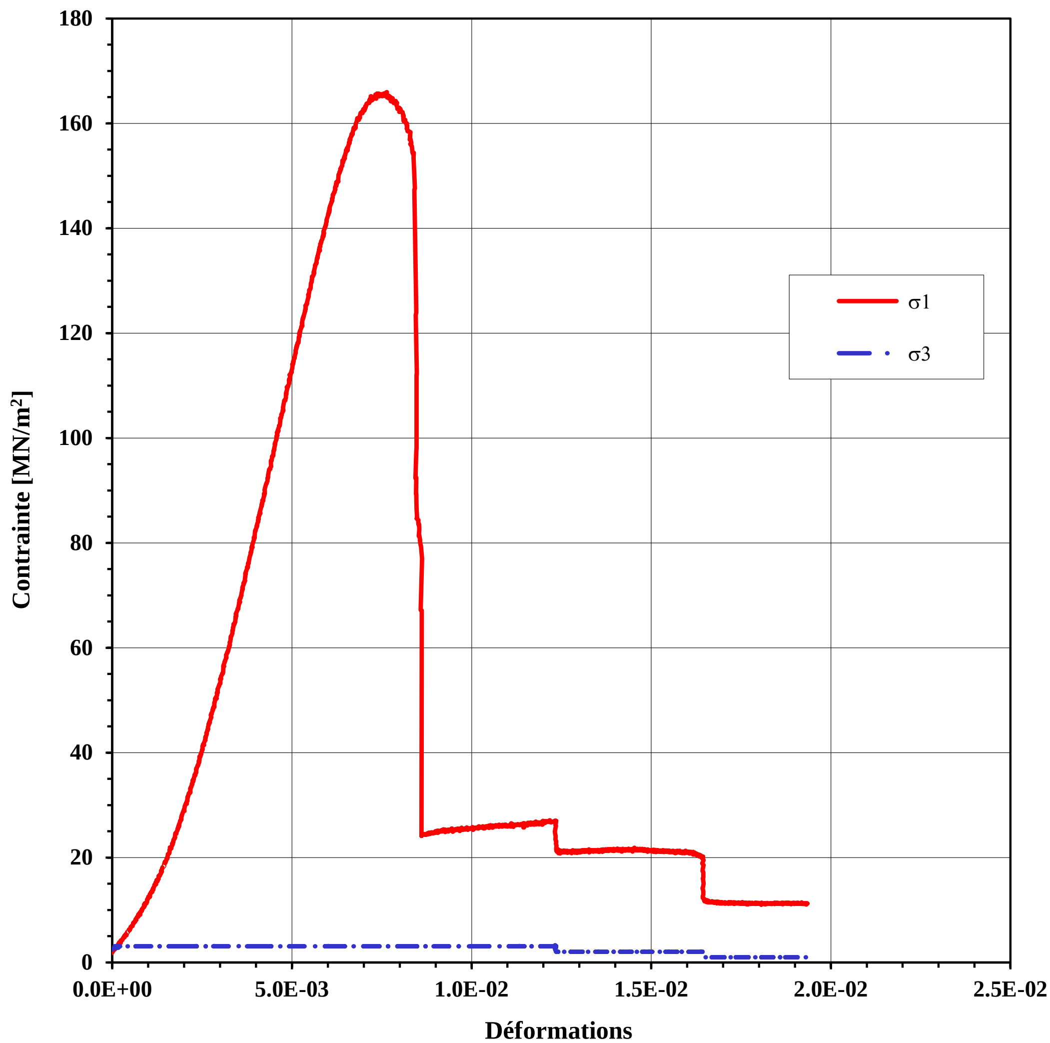
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kd-ZT3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m³]	w [%]	Ep50% [MN/m²]	ν [-]	σ_{max} [MN/m²]
116.8	54.4	2.80	-	29500	-	166.0



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

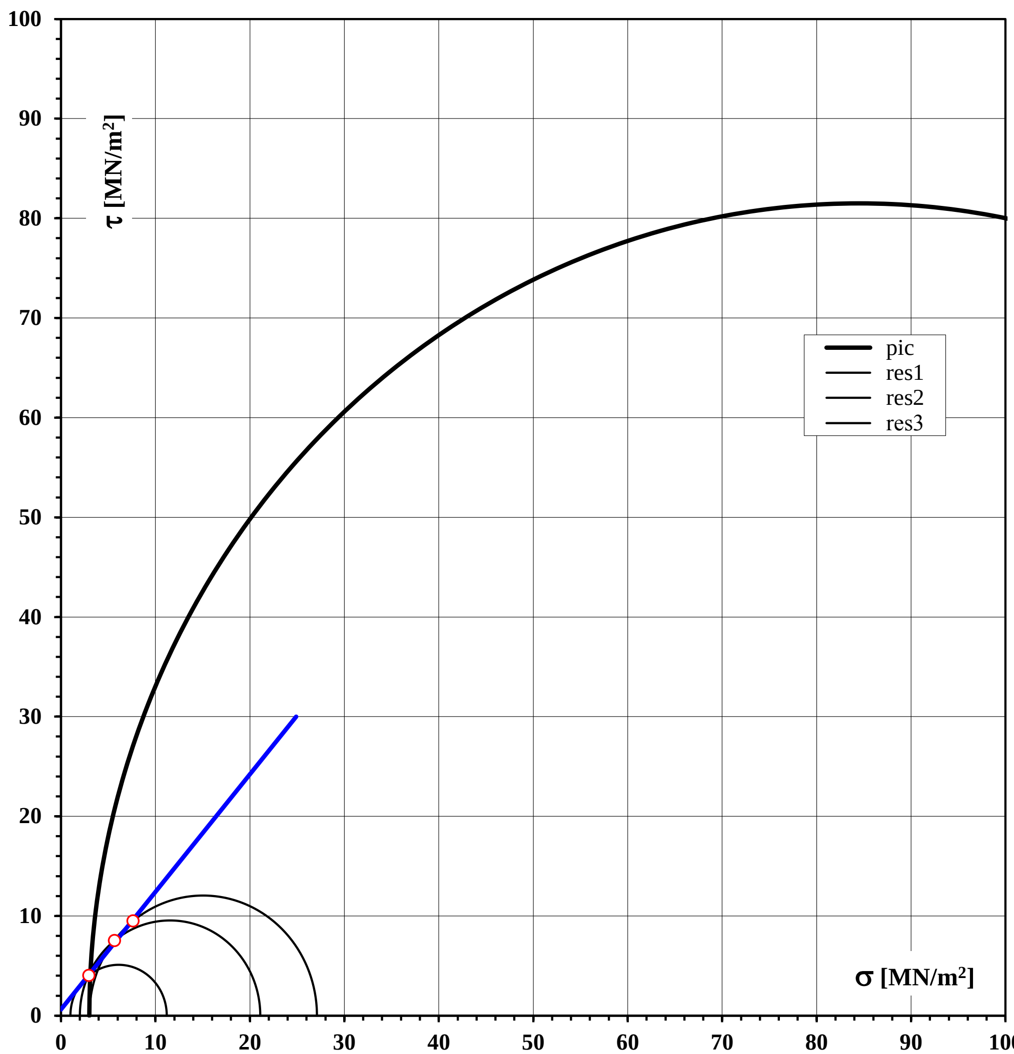
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Kd-ZT3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1	val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	3.0	166.0	MN/m2	3.0	27.1	2.0	21.1	1.0	11.2	50.0	0.6



Observations:

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R0839-Kd-ZT3_Triax.xlsx

LEMR
LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

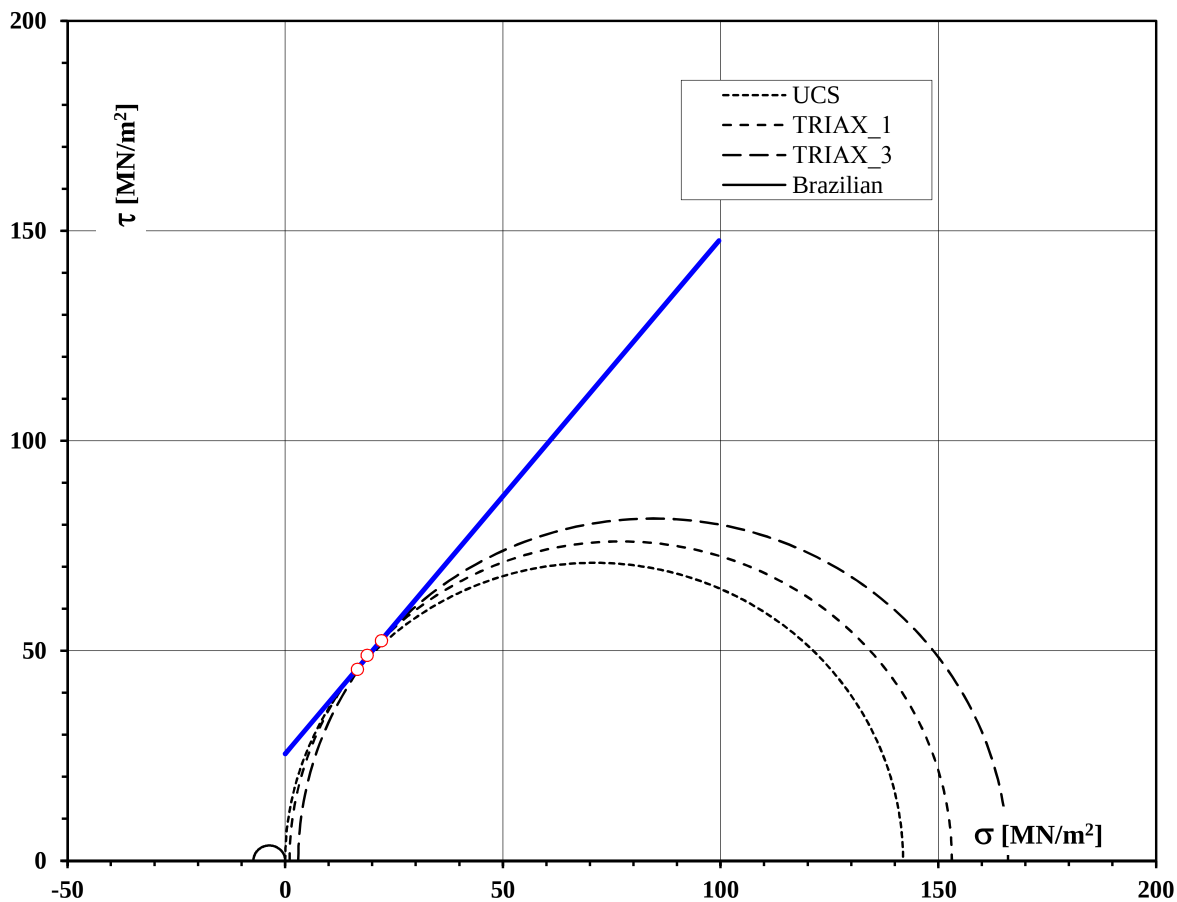
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
ZT1, ZT3	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
diorite of North America (Kd)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone	[signature]	BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	141.9	1.0	153.1	3.0	166.0	-7.3	0.0	51.0	25.5



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

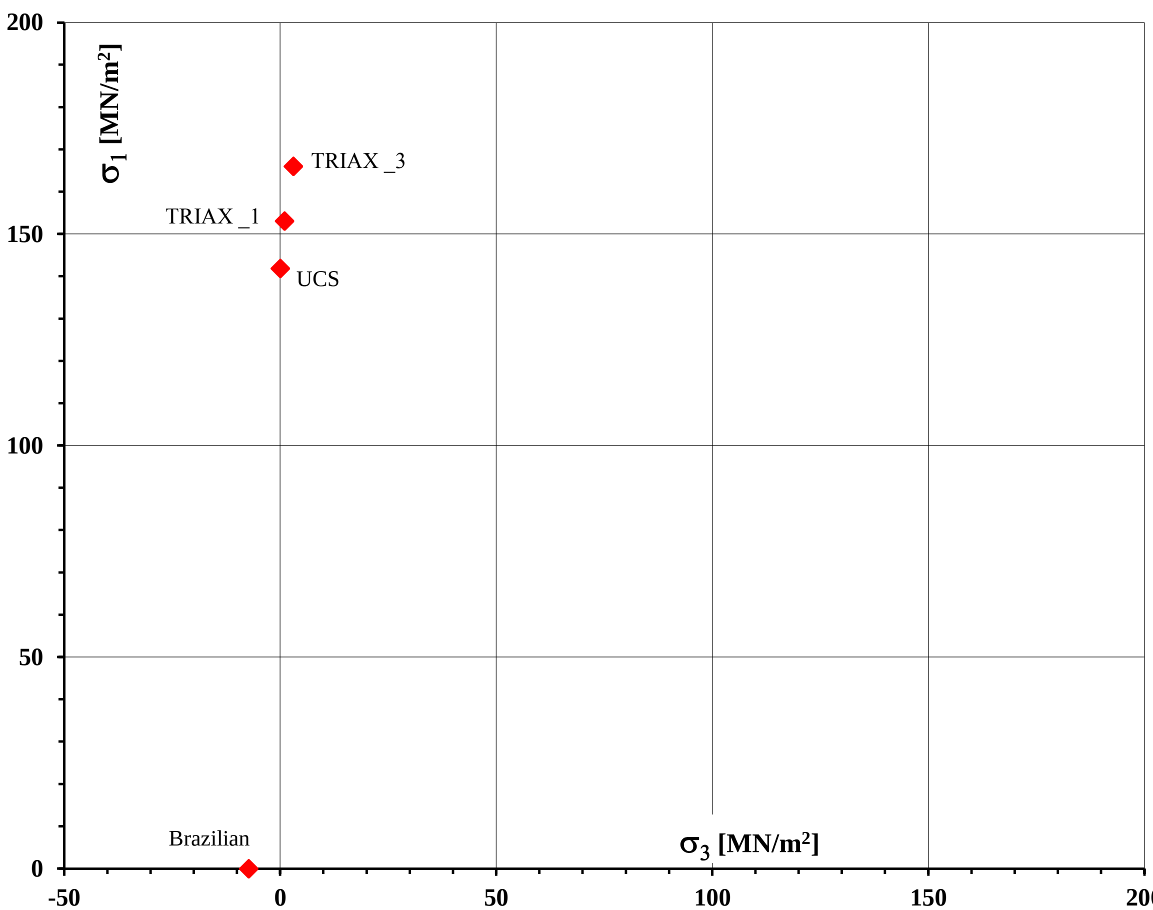
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
ZT1, ZT3	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
diorite of North America (Kd)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone		BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	141.9	1.0	153.1	3.0	166.0	-7.3	0.0	51.0	25.6



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

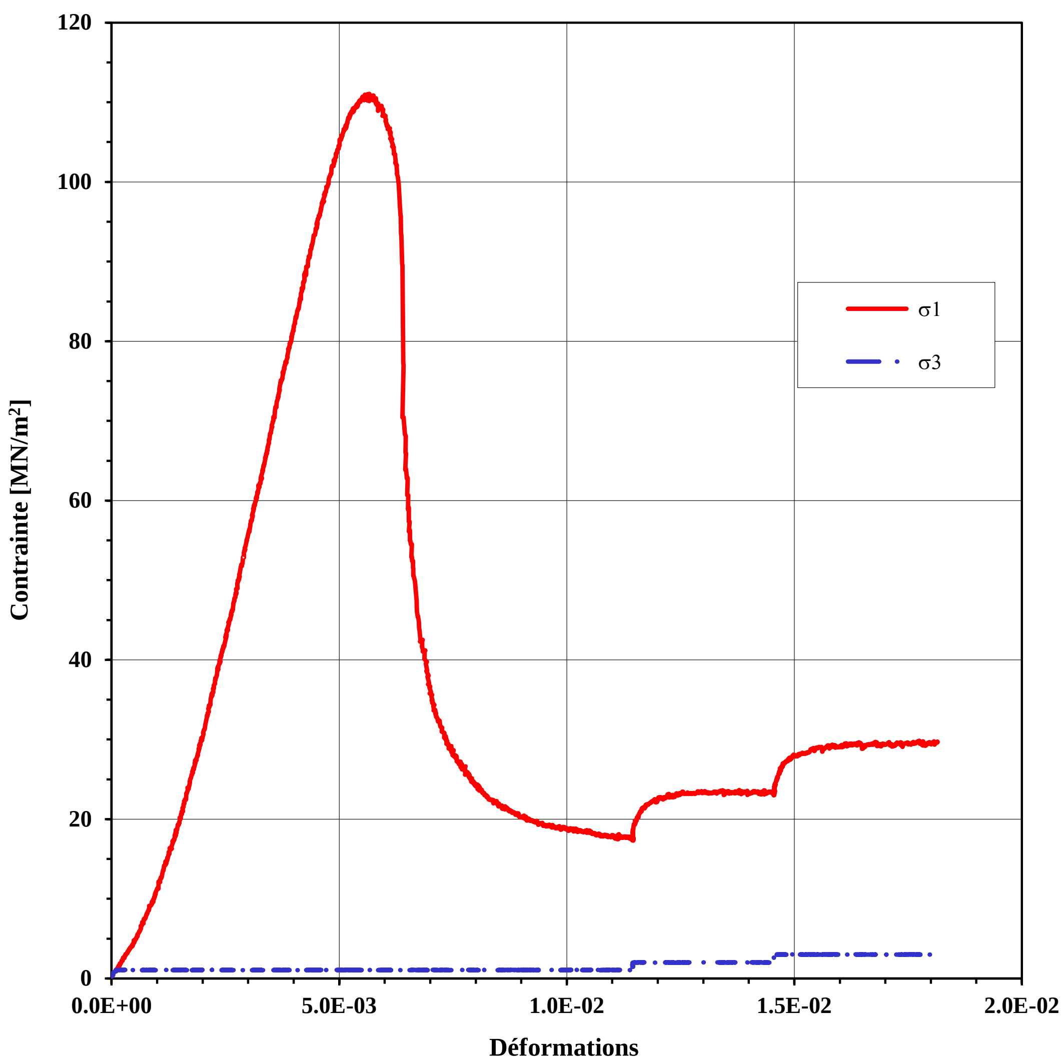
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Ks-IC1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
119.3	54.3	2.77	-	24700	-	111.1



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

LMS-LMR 75 ANS 1935-2010

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

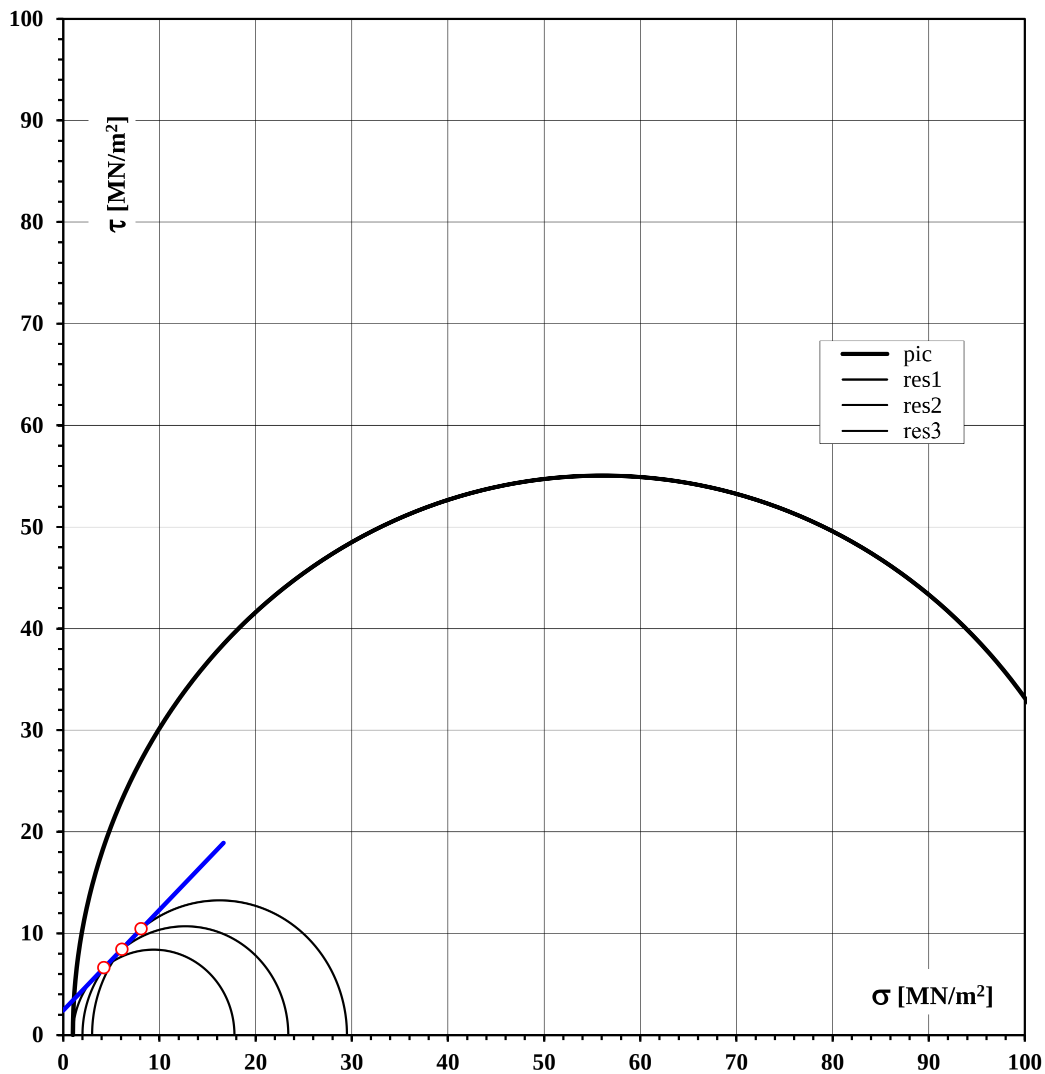
No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Ks-IC1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1
MN/m2	1.0	111.1

val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	1.0	17.8	2.0	23.4	3.0	29.5	45.0	2.4



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

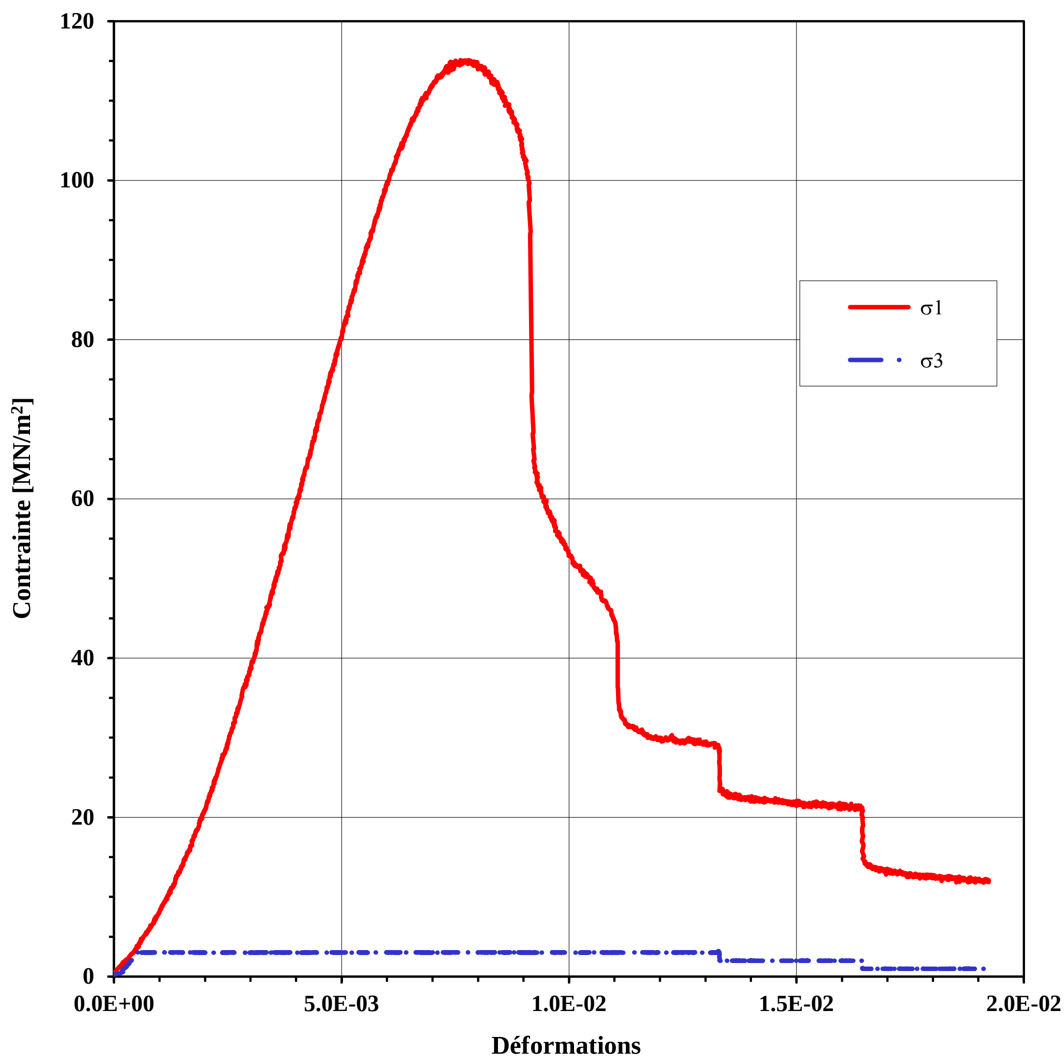
ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette		Titre de l'étude		Commettant		
				nom		adresse
R0839-Ks-IC3		ESSAIS UNIL-USGS		UNIL		LAUSANNE
No sond.	Prof. [m]	Nature échantillon		Echantillon prélevé par	Date réception	Date essai
Ks	-	SENTINEL GRANODIORITE		COMMETTANT	08.07.14	09.09.14
Mode conservation		Mode préparation éprouvette		Ingénieur responsable nom	signature	Opérat.
NATUREL		SCIE, RECTIFIE		F. SANDRONE		BF

Haut. [mm]	Diam. [mm]	ρ [t/m³]	w [%]	Ep50% [MN/m²]	ν [-]	σ_{max} [MN/m²]
119.0	54.4	2.76	-	20000	-	115.1



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

LMS-LMR 75 ANS 1935-2010

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

ESSAI TRIAXIAL

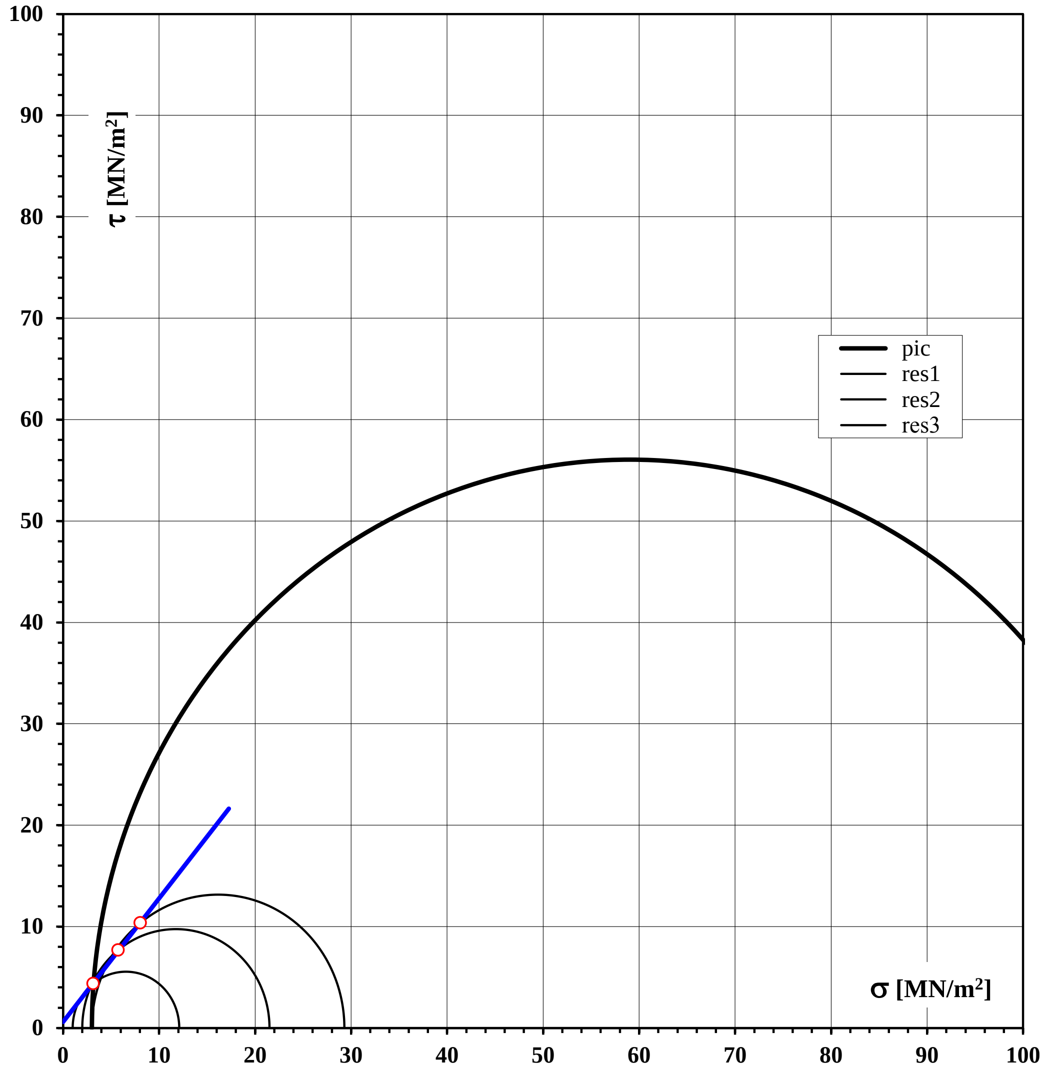
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

No éprouvette		Titre de l'étude	Commettant nom	Commettant adresse
R0839-Ks-IC3		ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	09.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		BF

val. pic	σ_3	σ_1	val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	3.0	115.1	MN/m2	3.0	29.3	2.0	21.5	1.0	12.1	51.0	0.6



Observations:

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

LEMR LABORATORY OF EXPERIMENTAL ROCK MECHANICS

EPFL

ESSAI TRIAXIAL

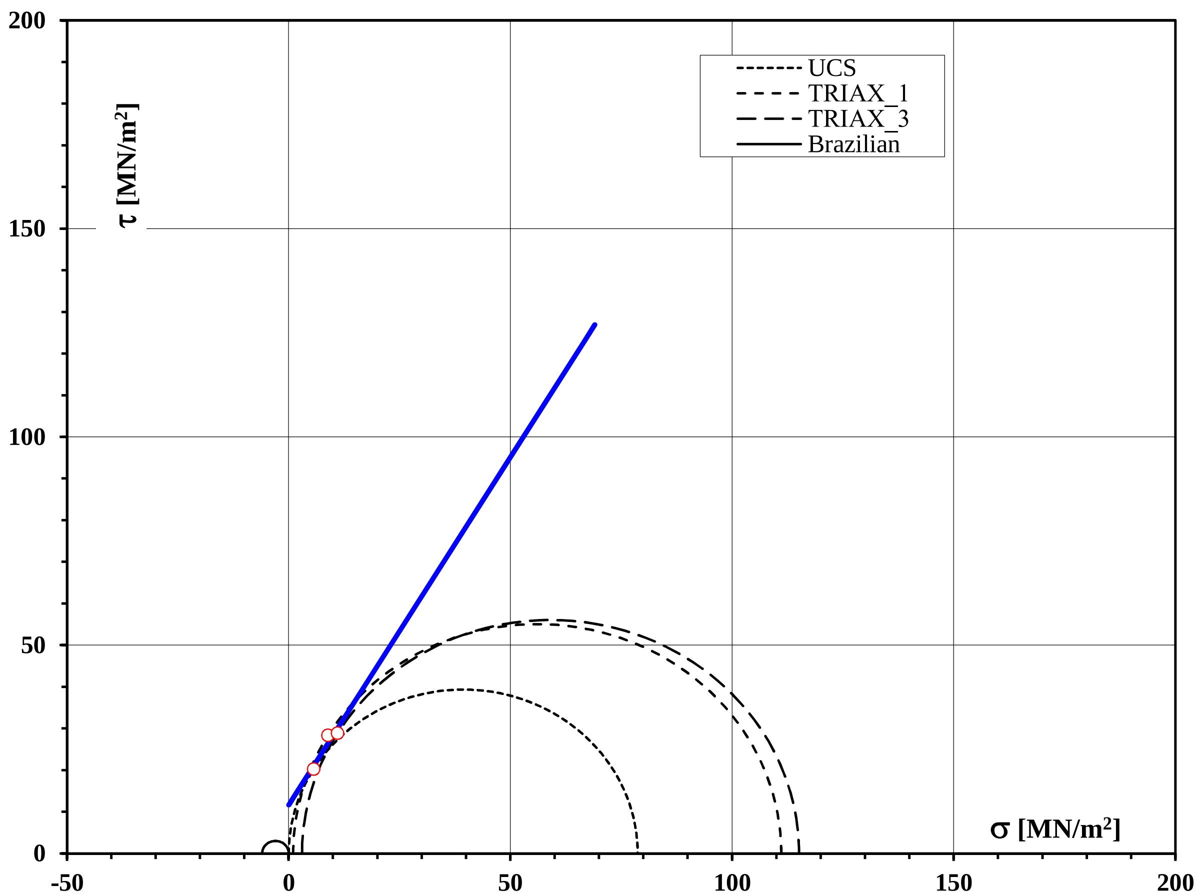
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
IC1, IC3, IC4	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Sentinel Granodiorite (Ks)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone		BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	78.7	1.0	111.1	3.0	115.1	-6.0	0.0	59.0	11.6



Observations:

LEMR LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

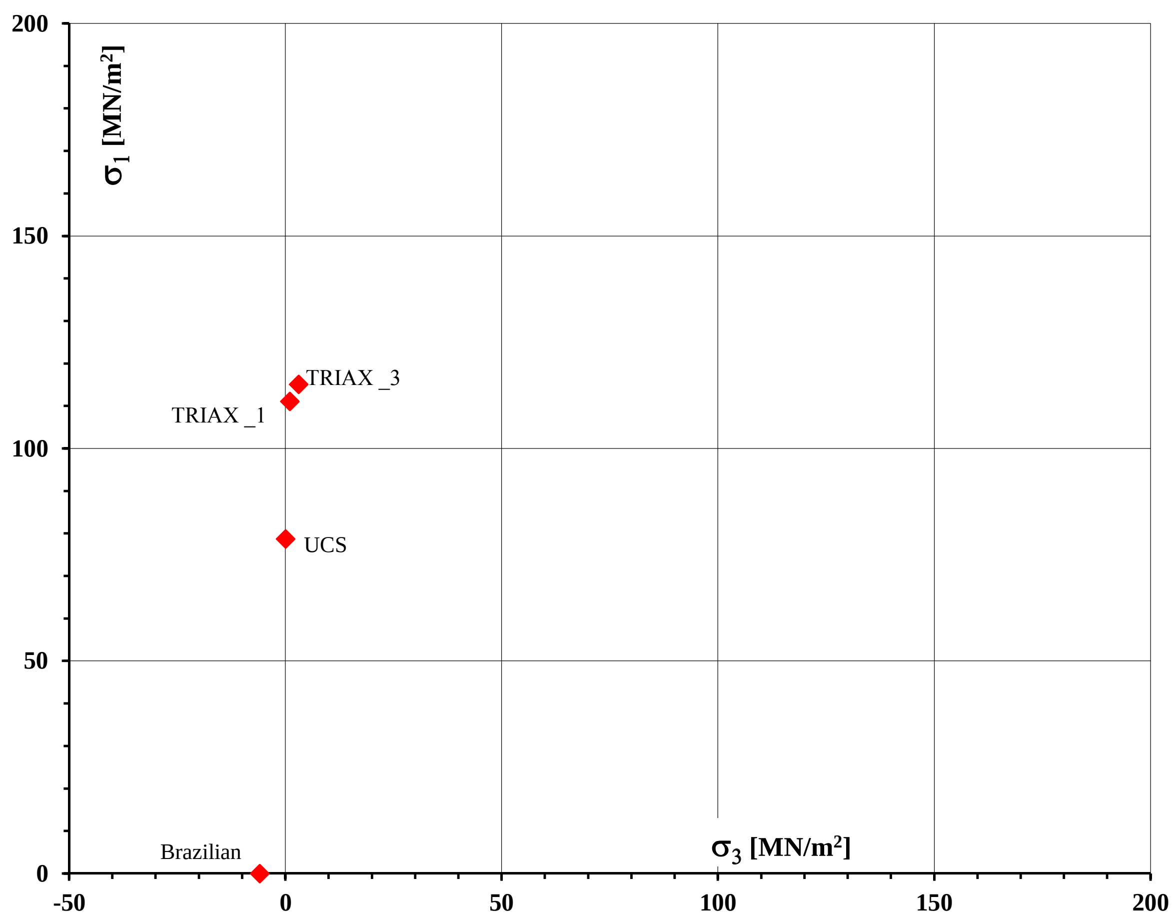
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
IC1, IC3, IC4	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Sentinel Granodiorite (Ks)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone	[signature]	BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	78.7	1.0	111.1	3.0	115.1	-6.0	0.0	56.0	13.4



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

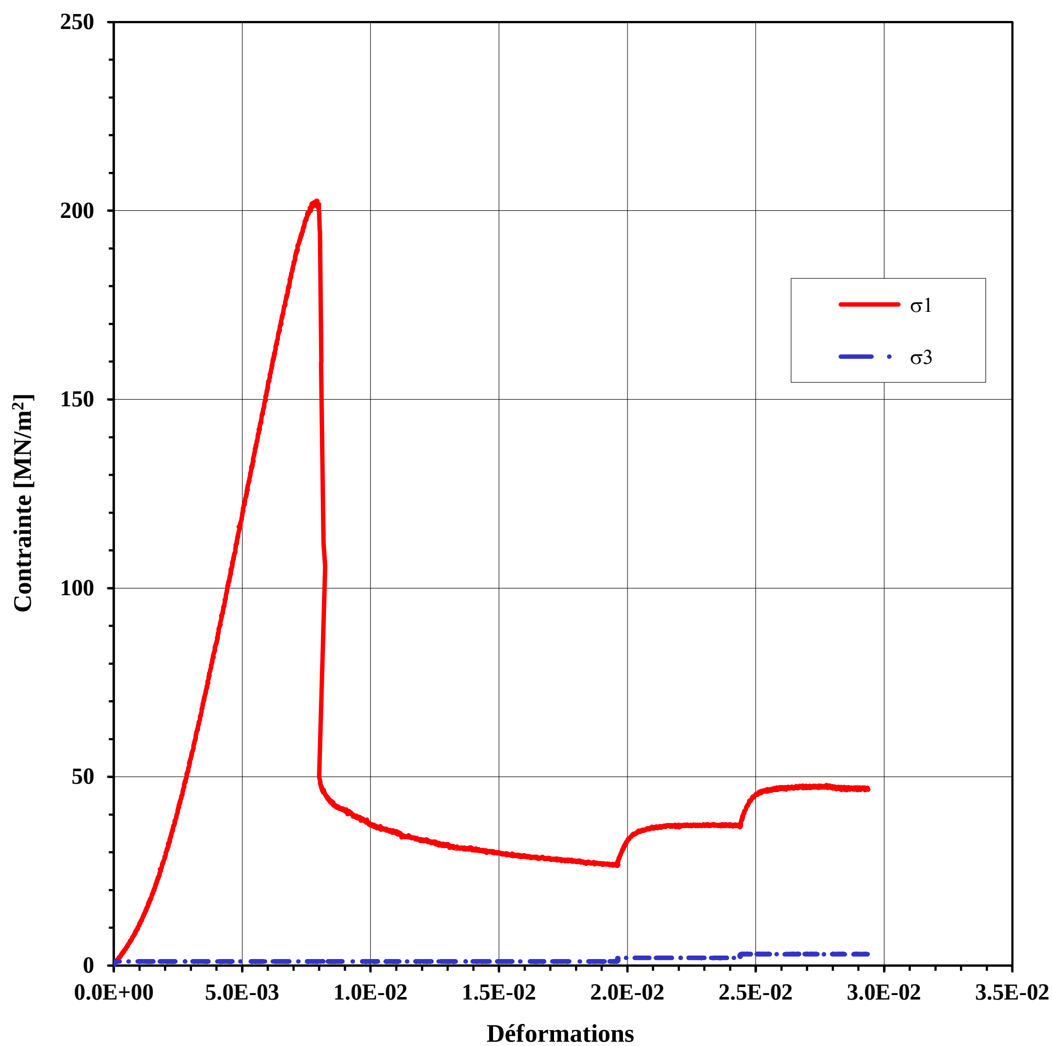
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-Khd-RP2	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
116.5	54.2	2.64	-	31600	-	202.7



Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

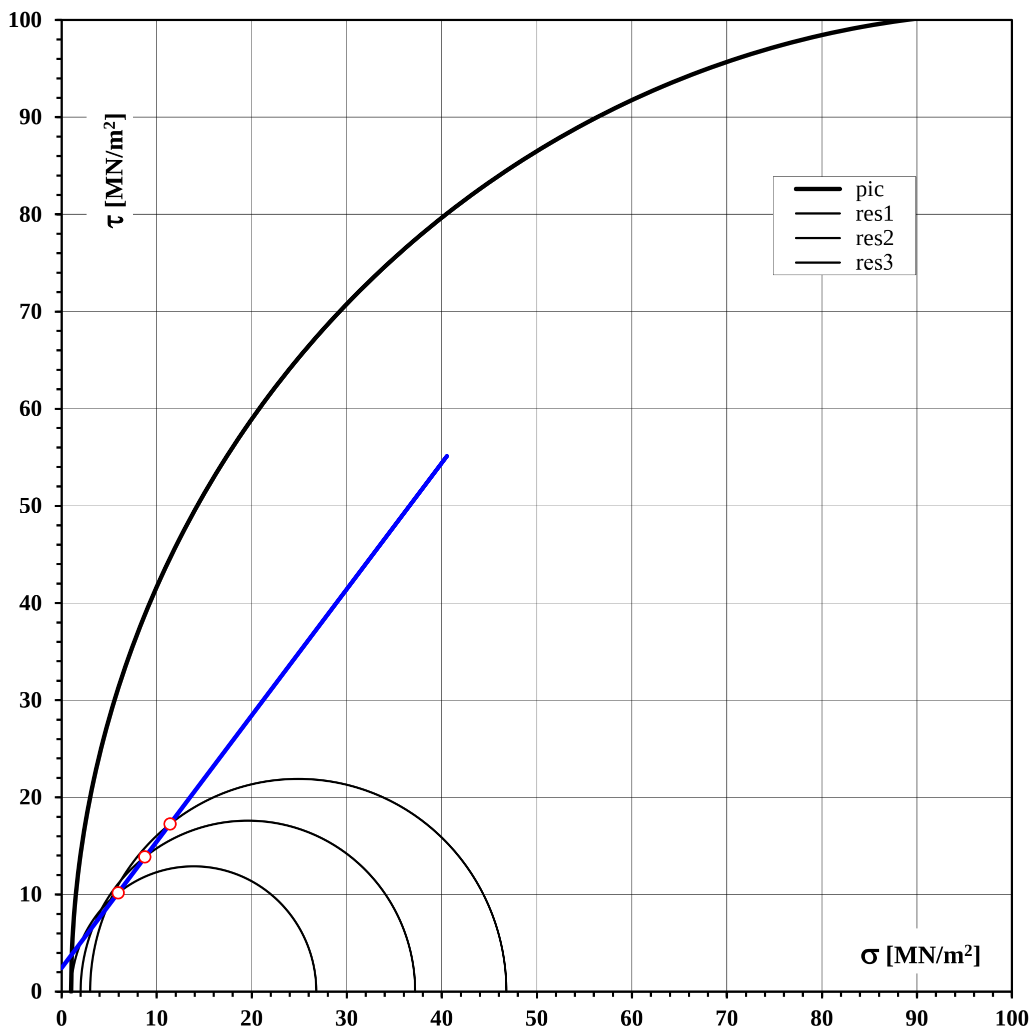
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-Khd-RP2	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

val. pic	σ_3	σ_1	val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	1.0	202.7	MN/m2	1.0	26.8	2.0	37.2	3.0	46.8	52.0	2.4



Observations:

LEMR
LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

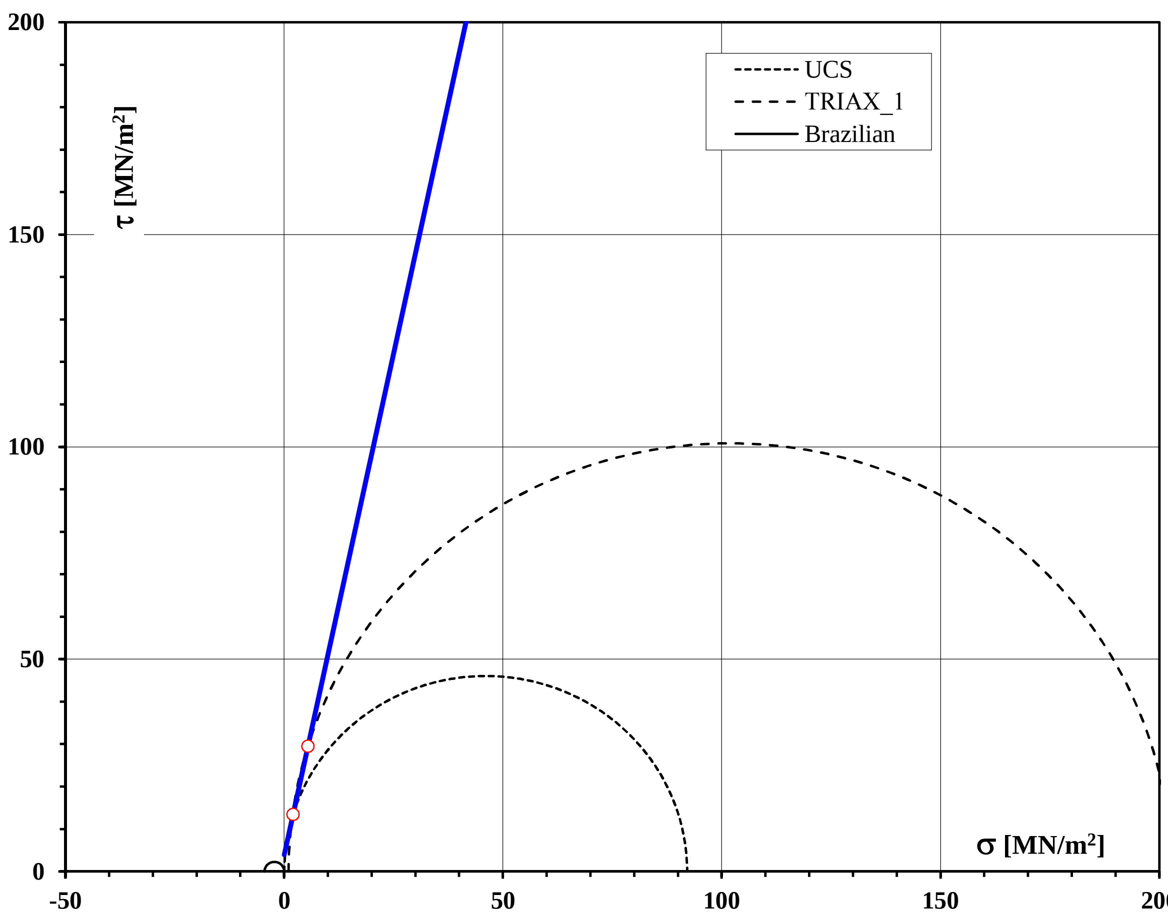
EPFL

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
RP2 / RP4	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Half Dome Granodiorite (Khd)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone	[signature]	BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic MN/m2	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
	0.0	92.1	1.0	202.7	0.0	0.0	-4.5	0.0	78.0	4.0



Observations:

LEMR
LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

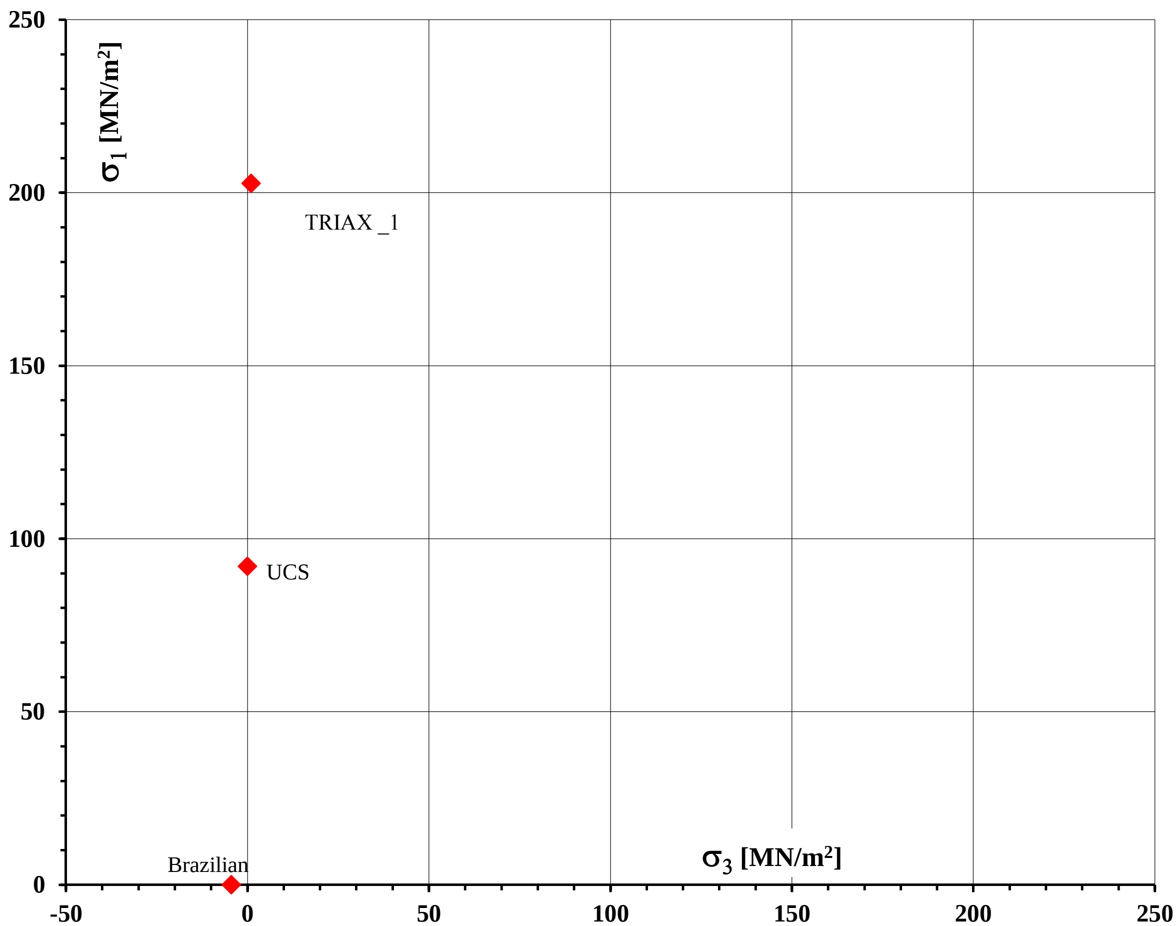
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
RP2 / RP4	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Half Dome Granodiorite (Khd)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone	[signature]	BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	92.1	1.0	202.7	0.0	0.0	-4.5	0.0	79.0	4.4



Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

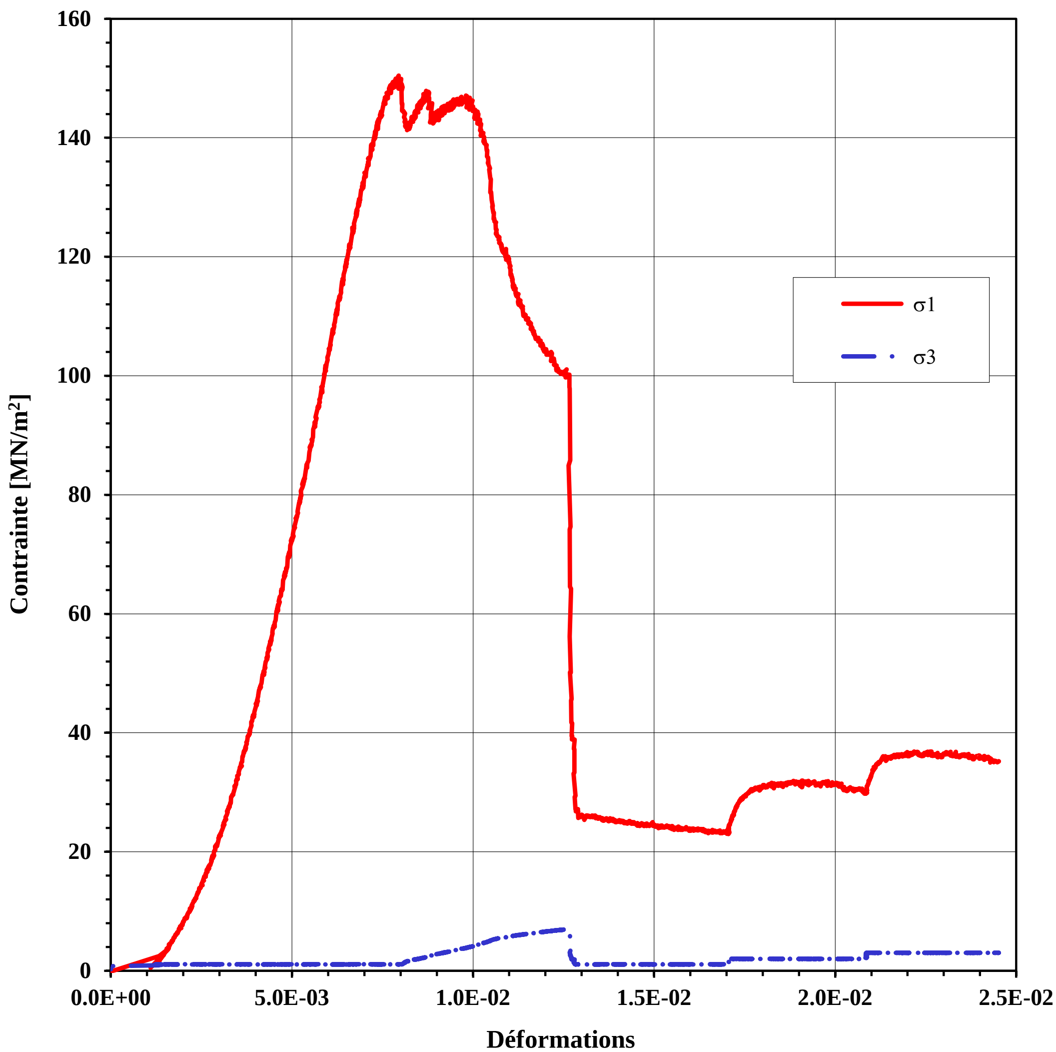
ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette		Titre de l'étude	Commettant: nom	Commettant: adresse	
R0839-Khd-ML1		ESSAIS UNIL-USGS	UNIL	LAUSANNE	
No sond.	**Prof. [m]**	**Nature échantillon**	**Echantillon prélevé par**	**Date réception**	**Date essai**
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	02.09.14
Mode conservation	**Mode préparation éprouvette**		**Ingénieur responsable: nom**	**signature**	**Opérat.**
NATUREL	SCIE, RECTIFIE		F. SANDRONE		LG

Haut. [mm]	Diam. [mm]	ρ [t/m^3]	w [%]	Ep50% [MN/m^2]	ν [-]	σ_{max} [MN/m^2]
116.5	54.2	2.66	-	32000	-	150.4



Observations: The results show an unexpected increase of the confinement immediately after the sample broke at peak stress; this was due to a small problem in the control of the oil pressure but did not affect the results nor the behavior of the sample for the following steps of confinement.

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

ESSAI TRIAXIAL

Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.620

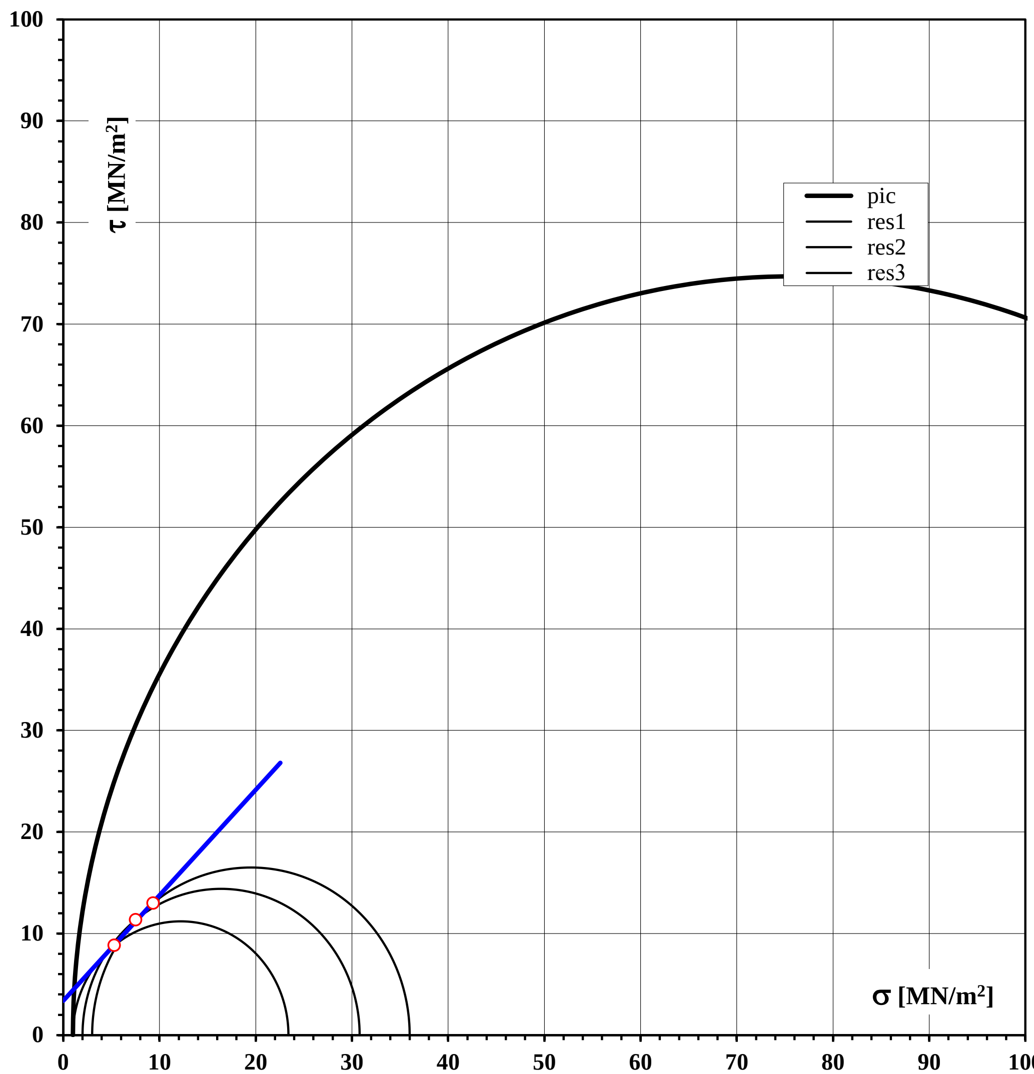
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant: nom	Commettant: adresse
R0839-Khd-ML1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	02.09.14

Mode conservation	Mode préparation éprouvette	Ingénieur responsable: nom	Ingénieur responsable: signature	Opérat.
NATUREL	SCIE, RECTIFIE	F. SANDRONE		LG

val. pic	σ_3	σ_1	val. res.	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_r [°]	c_r [MN/m^2]
MN/m2	1.0	150.4	MN/m2	1.0	23.4	2.0	30.8	3.0	36.0	46.0	3.4



Observations:

LEMR LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

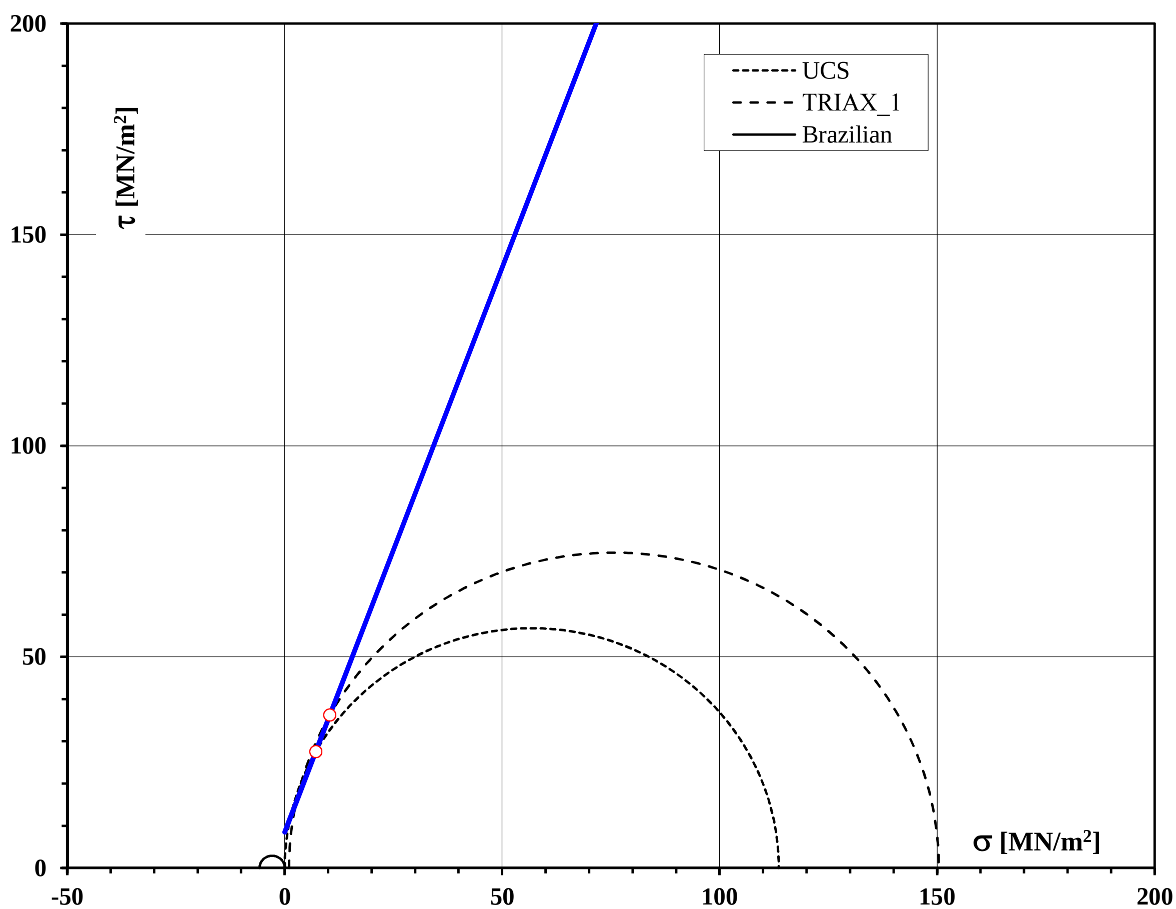
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
ML1	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Half Dome Granodiorite (Khd)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone		BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	113.6	1.0	150.4	0.0	0.0	-5.8	0.0	70.0	8.5



Observations:

LEMR LABORATORY OF EXPERIMENTAL ROCK MECHANICS

LABORATOIRE EXPERIMENTAL DE MECANIQUE DES ROCHES

EPFL

ESSAI TRIAXIAL

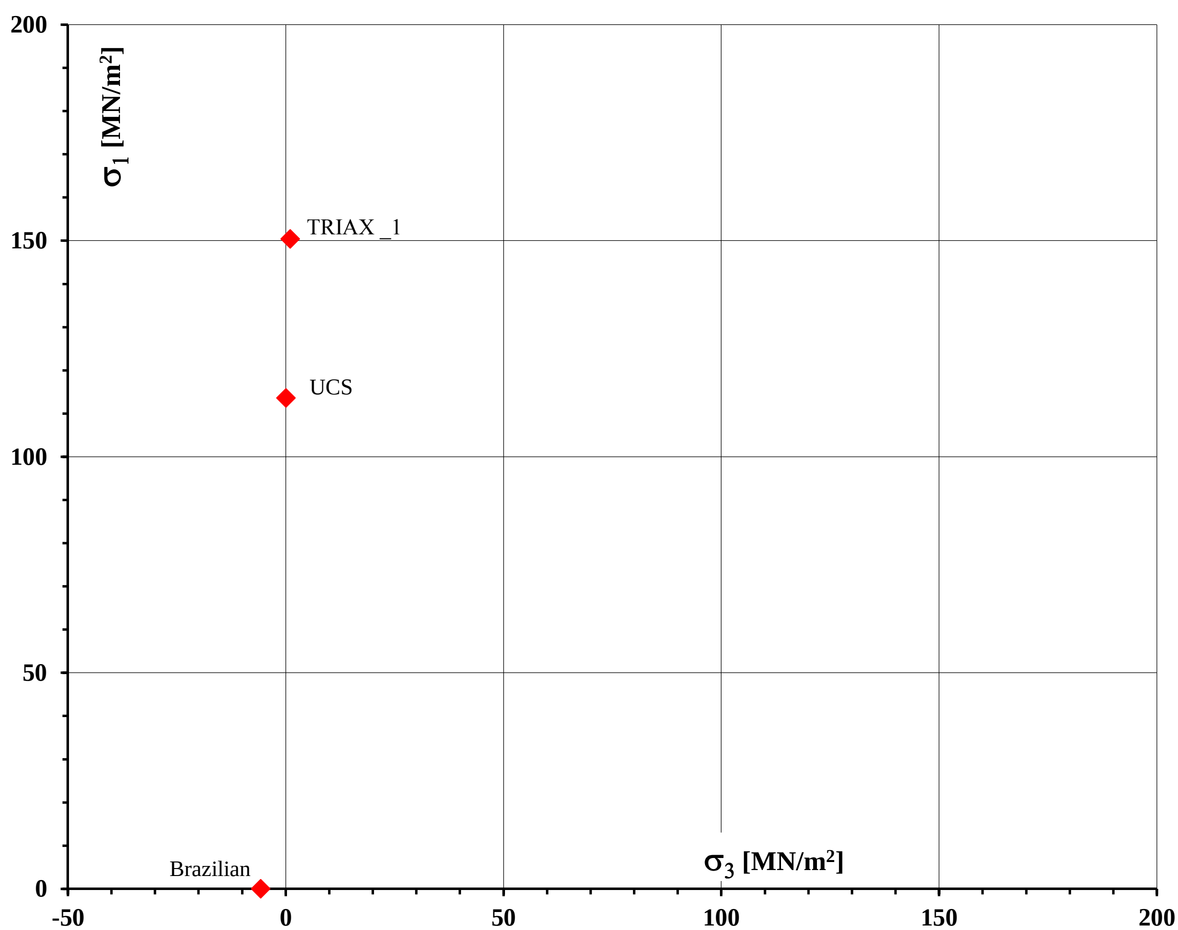
Exécuté selon la norme ASTM D 2664-86 et LMS+R ER.321

No éprouvettes	Titre de l'étude	Commettant	
		nom	adresse
ML1	ESSAIS UNIL-USGS	UNIL	Lausanne

Nature échantillon	Date reception	Date essai
Half Dome Granodiorite (Khd)	08.07.14	-

Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérateur
		nom	signature	
NATUREL	SCIE, RECTIFIE	F. Sandrone	[signature]	BF

	UCS		Triax_1		Triax_3		Brazilian			
val. pic	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	ϕ_p [°]	c_p [MN/m^2]
MN/m2	0.0	113.6	1.0	150.4	0.0	0.0	-5.8	0.0	71.0	9.4



Observations:

Sample R0839-Kec-CS1-Triax before

Sample R0839-Kec-CS1-Triax after

Sample R0839-Kec-CS3-Triax before

Sample R0839-Kec-CS3-Triax after

Sample R0839-Kgb-NT1-Triax before

Sample R0839-Kgb-NT1-Triax after

Sample R0839-Kgb-NT3-Triax before

Sample R0839-Kgb-NT3-Triax after

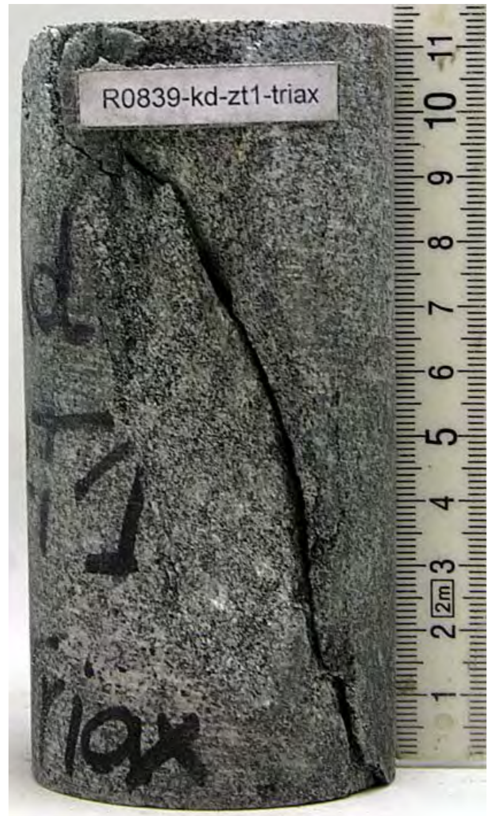
Sample R0839-Kt-RA1-Triax before

Sample R0839-Kt-RA1-Triax after

Sample R0839-Kt-RA4-Triax before

Sample R0839-Kt-RA4-Triax after

Sample R0839-Kd-ZT1-Triax before



Sample R0839-Kd-ZT1-Triax after

Sample R0839-Kd-ZT3-Triax before

Sample R0839-Kd-ZT3-Triax after

Sample R0839-Ks-IC1-Triax before

Sample R0839-Ks-IC1-Triax after

Sample R0839-Ks-IC3-Triax before

Sample R0839-Ks-IC3-Triax after

Sample R0839-Khd-RP2-Triax before

Sample R0839-Khd-RP2-Triax after

Sample R0839-Khd-ML1-Triax before

Sample R0839-Khd-ML1-Triax after

Appendix 3. Chevron Bend (CB) Method Mode I Fracture Toughness Strength Test Results and Sample Photographs

This appendix contains the stress-strain results and photographs of each failed sample for each of the nine chevron bend fracture toughness tests performed on the Yosemite Valley rock samples. Because the testing was performed at the French-speaking Laboratoires de Mecanique des Sols et des Roches (Soil and Rock Mechanics Laboratory) at the École Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology Lausanne, EPFL) in Lausanne, Switzerland, the data sheets containing the results are in French. A key to pertinent information contained on these forms is included here.

SOIL AND ROCK MECHANICS LABORATORY

FRACTURE TOUGHNESS

Executed according to the standard ISRM (1988) and LMS+R ER.540

Sample Number		Title of Study	Client	
			Name	Address
R0839-khd-ML1		ESSAIS UNIL - USGS	UNIL	LAUSANNE

Borehole Number	Depth [m]	Sample Description	Sample collected by	Date received	Date tested
khd ML1 c	-	HALF DOME GRANODIORITE	Client	08.07.14	18.06.15

Sample storage method	Sample preparation method	Engineer in charge		Operator
		Name	Signature	
NATUREL	DRILLING AND SAWING	F. SANDRONE		LG

Long. D [mm]	Diam. [mm]	Init. opening, t [mm]	a_0 [mm]	Orientation of schistosity/load	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PARALLELE	**1.32**

French

Deplacement vertical [mm]
Ouverture de la saignée [mm]
Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l’éprouvette testée. En outre, il fait partie d’une série d’essais, voir page “Rapport d’essais.”

English

Vertical displacement [mm]
Crack opening [mm]
These test results cannot be perfectly reproduced and only apply to the sample tested. In addition, the results are part of a series of tests—see the test report page.

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

LMS-LMR 75 ANS 1935-2010

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-kec-CS2	ESSAIS UNIL-USGS	UNIL	LAUSANNE

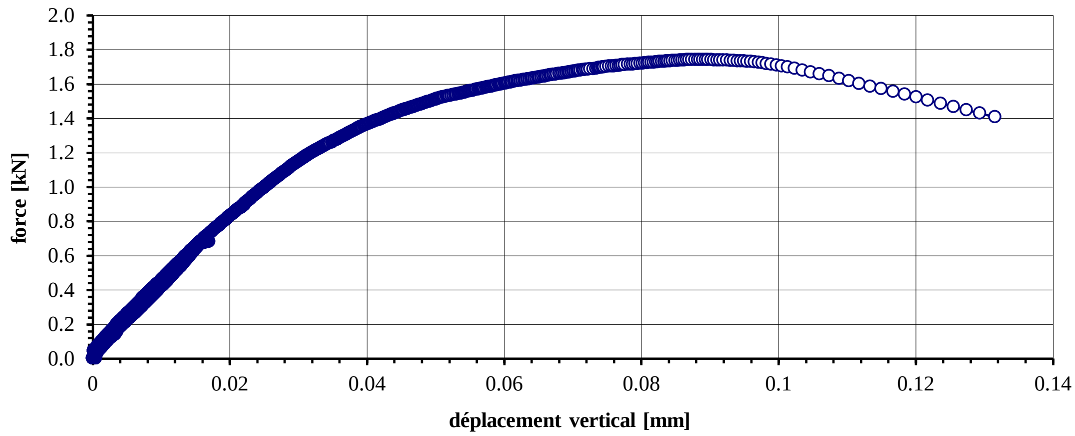
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
kec CS2	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	18.06.15

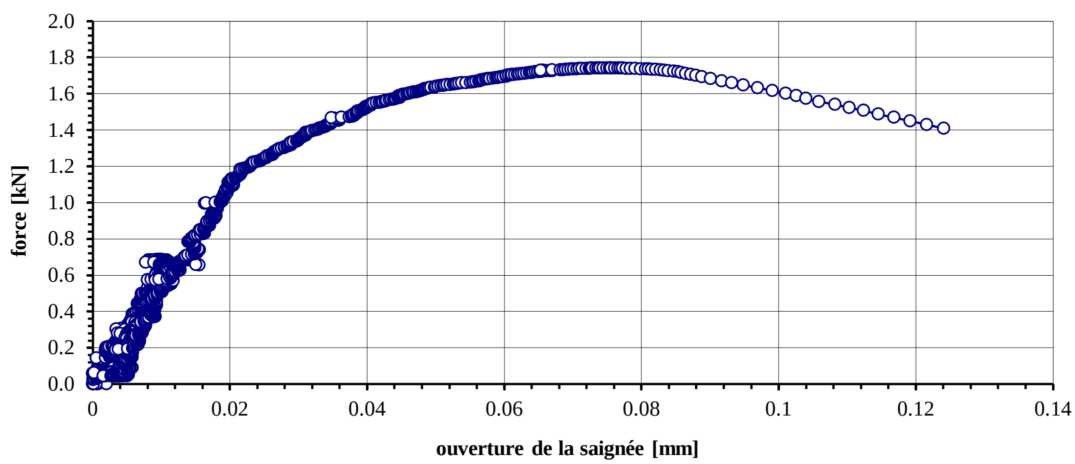
Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	CAROTTAGE + SCIAGE	F. SANDRONE		LG

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PERPENDICULAIRE	**1.61**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée — Page 1/1

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais" — ER.540 07/09

R0839-kec_CS2_per_toughness.xls

LMS-LMR 75 ANS 1935-2010

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

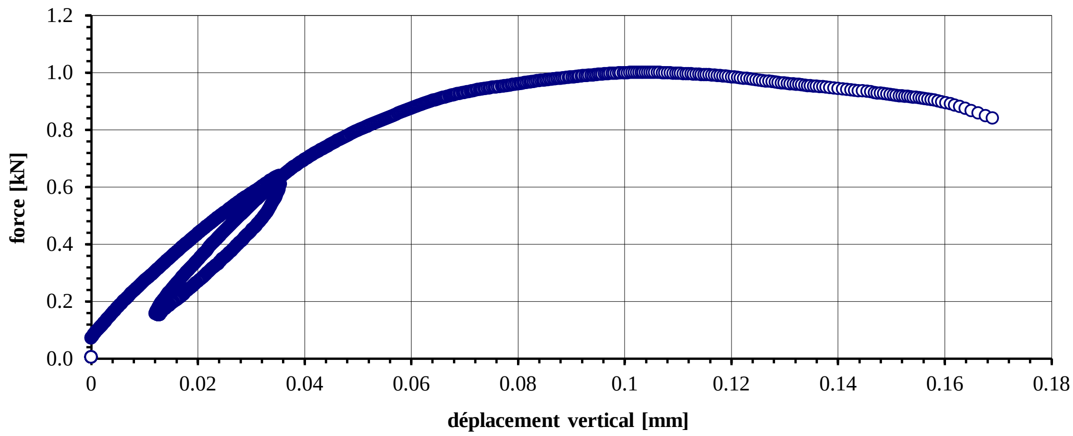
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

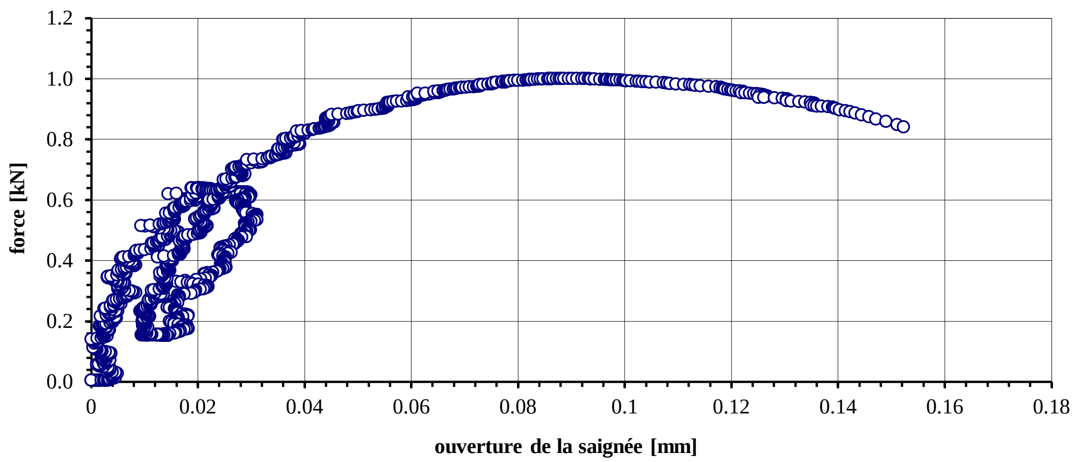
No éprouvette		Titre de l'étude	Commettant nom	Commettant adresse	
R0839-kec-CS3		ESSAIS UNIL-USGS	UNIL	LAUSANNE	
No sond.	**Prof. [m]**	**Nature échantillon**	**Echantillon prélevé par**	**Date réception**	**Date essai**
kec CS3	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	18.06.15
Mode conservation		**Mode préparation éprouvette**	**Ingénieur responsable nom**	**Ingénieur responsable signature**	**Opérat.**
NATUREL		CAROTTAGE + SCIAGE	F. SANDRONE	[signature]	BF

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PARALLELE	**0.93**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-kec-CS3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

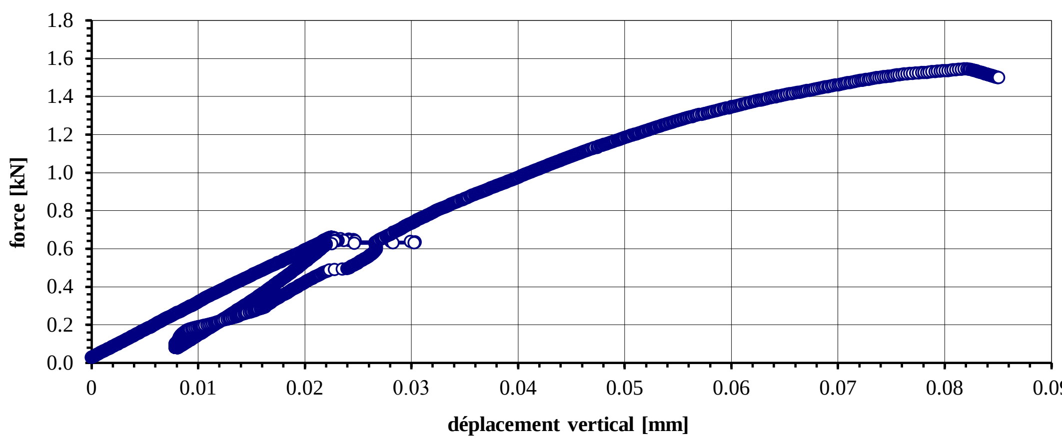
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
kec CS3	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	18.06.15

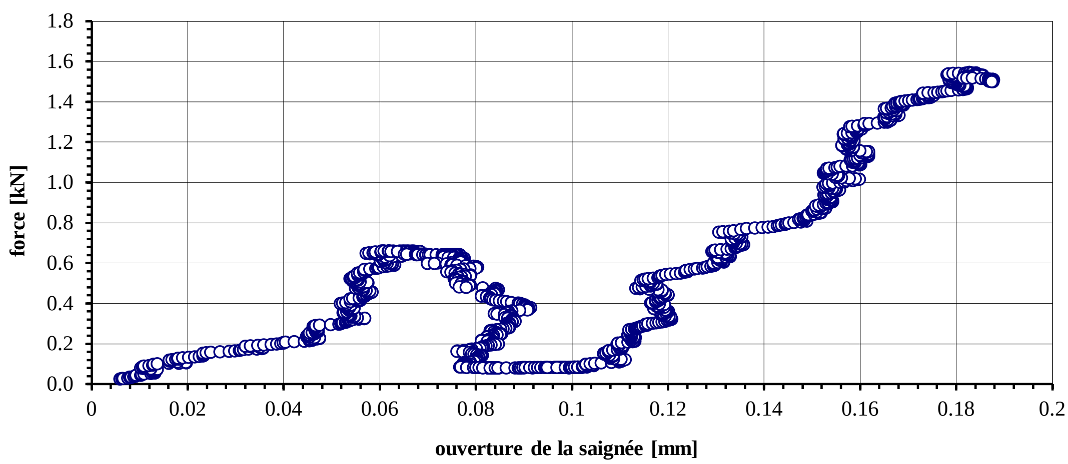
Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	CAROTTAGE + SCIAGE	F. SANDRONE		BF

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PERPENDICULAIRE	**1.43**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-kt-RA1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

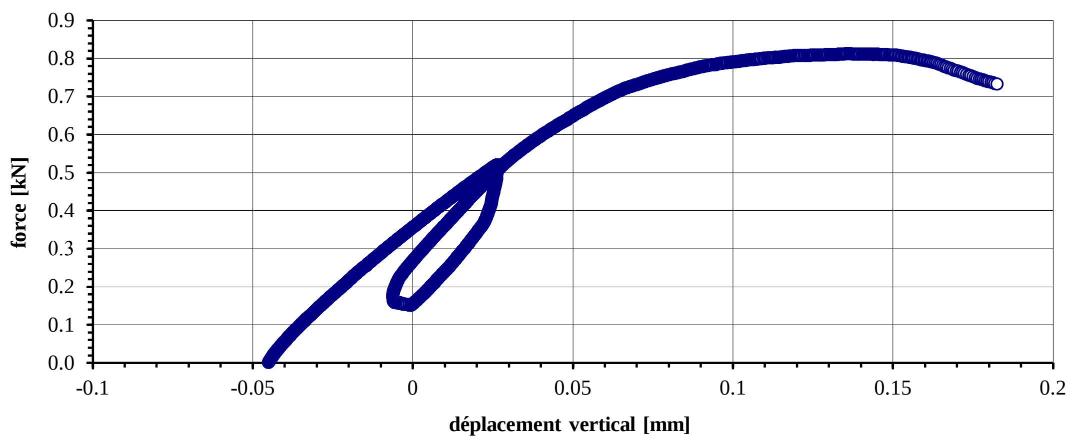
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
kt RA 1	-	TAFT GRANITE	COMMETTANT	08.07.14	18.06.15

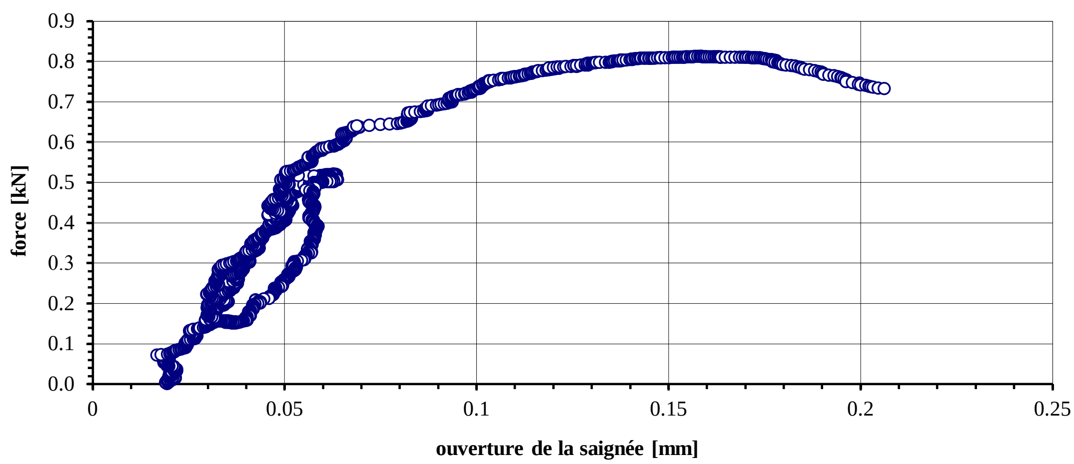
Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	CAROTTAGE + SCIAGE	F. SANDRONE		BF

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PARALLELE	**0.75**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-kt-RA3	ESSAIS UNIL-USGS	UNIL	LAUSANNE

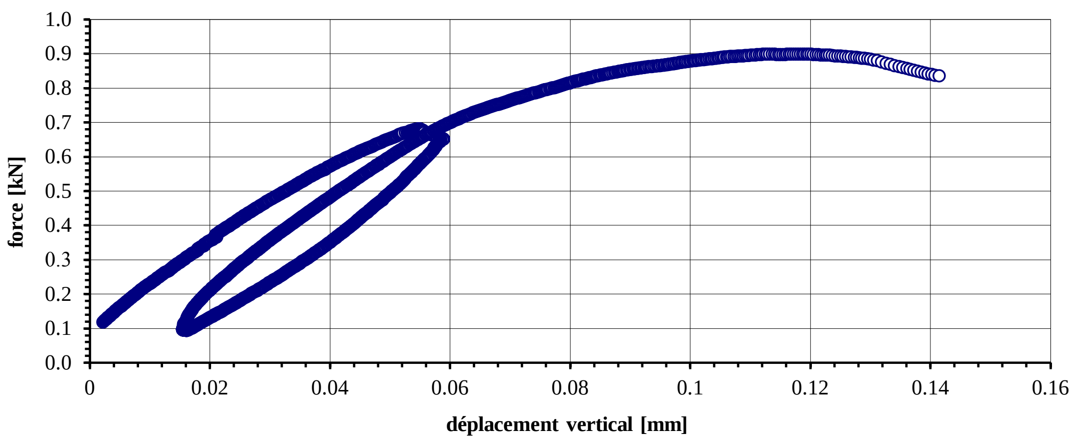
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
Kt-RA3	-	TAFT GRANITE	COMMETTANT	08.07.14	18.06.15

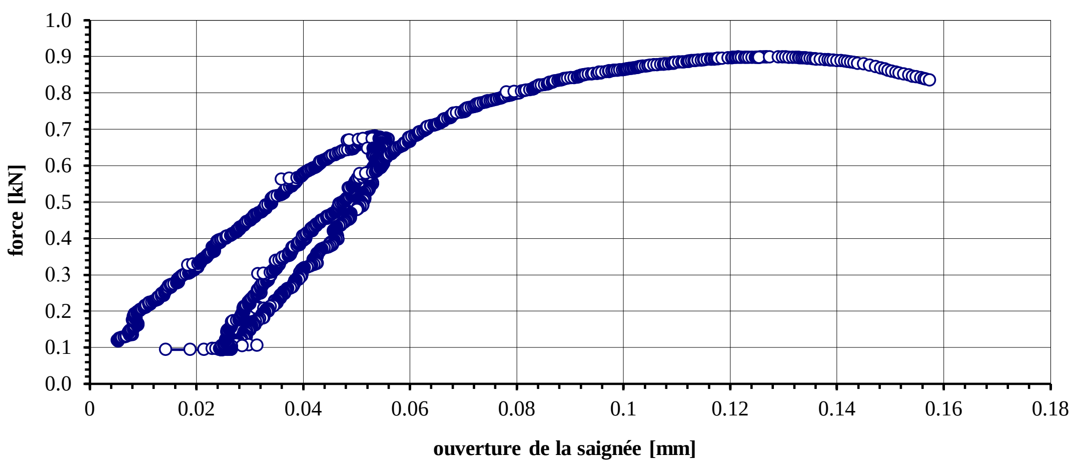
Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	CAROTTAGE + SCIAGE	F. SANDRONE		BF

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PARALLELE	**0.83**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-KT-ZT1	ESSAIS UNIL - USGS	UNIL	LAUSANNE

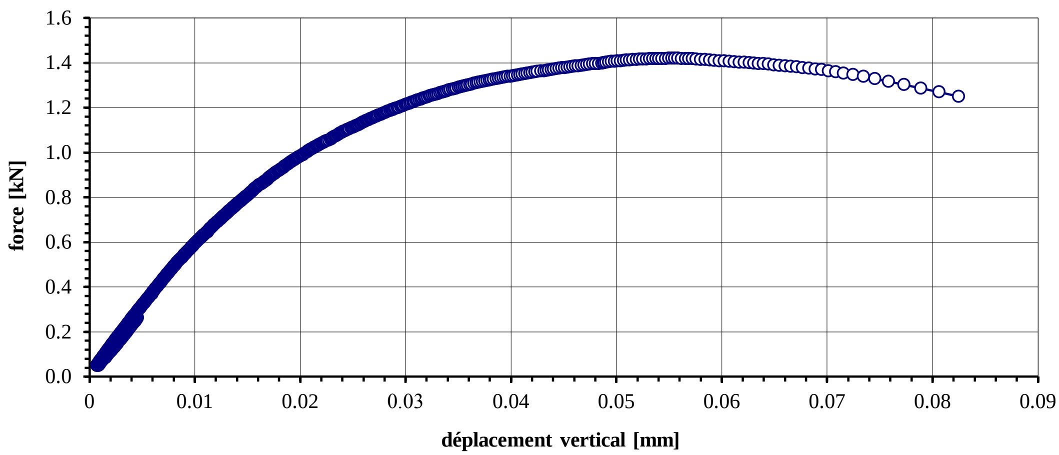
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
kt ZT 1	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	18.06.15

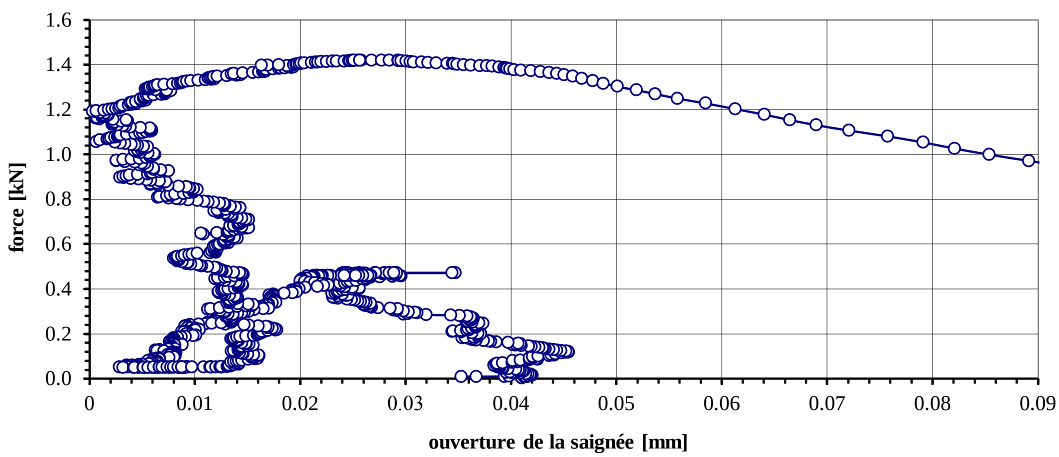
Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	CAROTTAGE + SCIAGE	F. SANDRONE		LG

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PERPENDICULAIRE	**1.32**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

LMS-LMR 75 ANS 1935-2010

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant	
		nom	adresse
R0839-khd-ML1	ESSAIS UNIL-USGS	UNIL	LAUSANNE

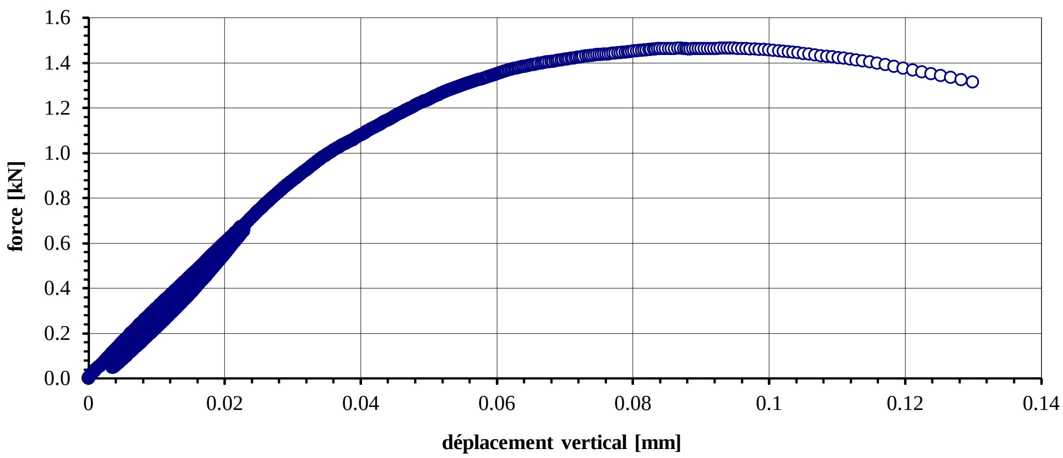
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
khd ML1 a	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	18.06.15

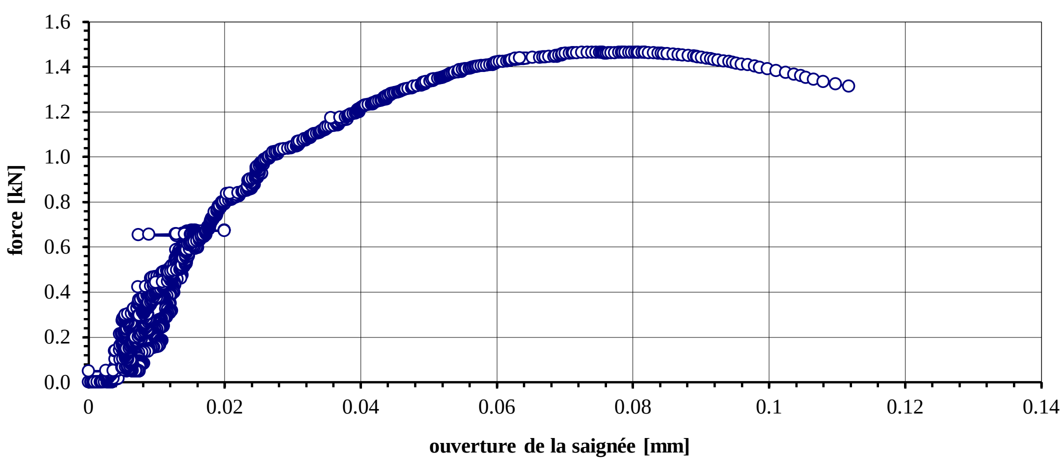
Mode conservation	Mode préparation éprouvette	Ingénieur responsable		Opérat.
		nom	signature	
NATUREL	CAROTTAGE + SCIAGE	F. SANDRONE		BF

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PARALLELE	**1.36**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

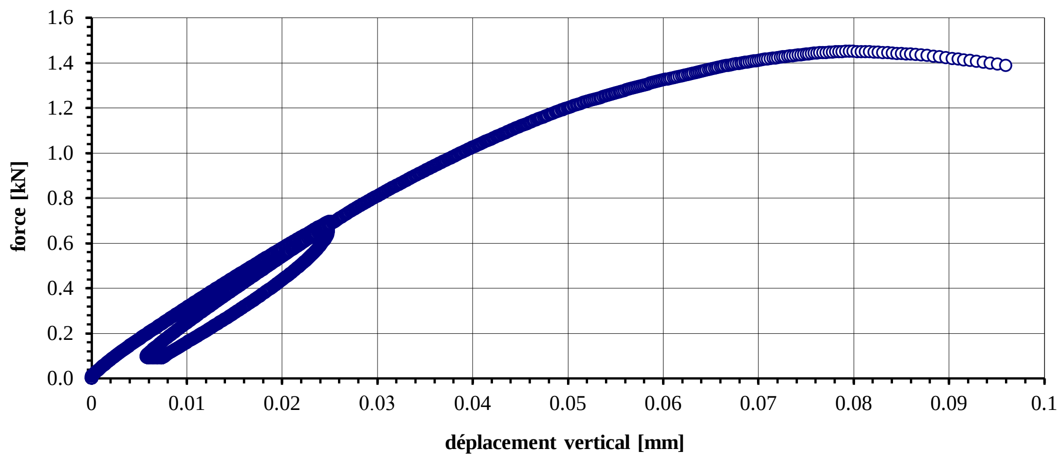
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

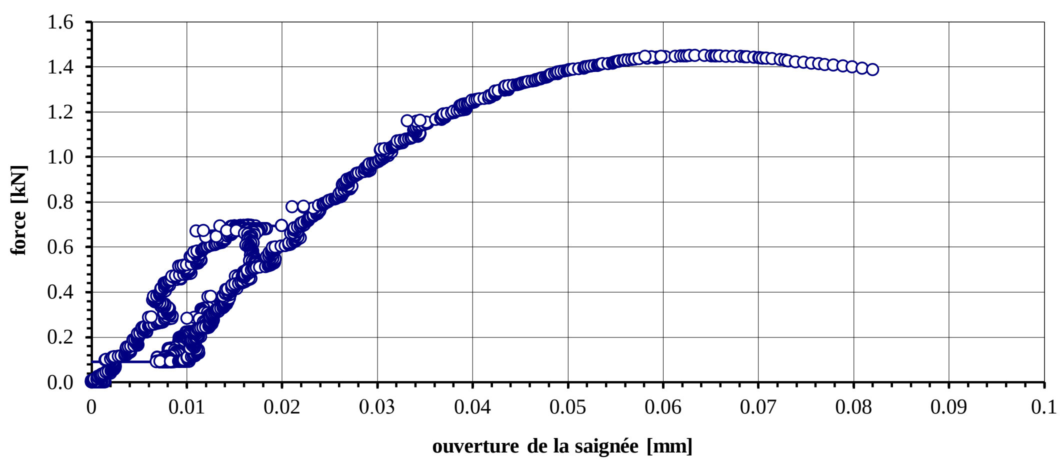
No éprouvette		Titre de l'étude		Commettant		
				nom		adresse
R0839-khd-ML1		ESSAIS UNIL-USGS		UNIL		LAUSANNE
No sond.	Prof. [m]	Nature échantillon		Echantillon prélevé par	Date réception	Date essai
khd ML1 b	-	HALF DOME GRANODIORITE		COMMETTANT	08.07.14	18.06.15
Mode conservation		Mode préparation éprouvette		Ingénieur responsable		Opérat.
				nom	signature	
NATUREL		CAROTTAGE + SCIAGE		F. SANDRONE		LG

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220	56	1.7	8.3	PARALLELE	**1.34**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

LMS-LMR 75 ANS 1935-2010

LABORATOIRES DE MECANIQUE DES SOLS ET DES ROCHES

TENACITE DE FRACTURE

Exécuté selon la recommandation ISRM (1988) et LMS+R ER.540

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No éprouvette	Titre de l'étude	Commettant nom	Commettant adresse
R0839-khd-ML1	ESSAIS UNIL - USGS	UNIL	LAUSANNE

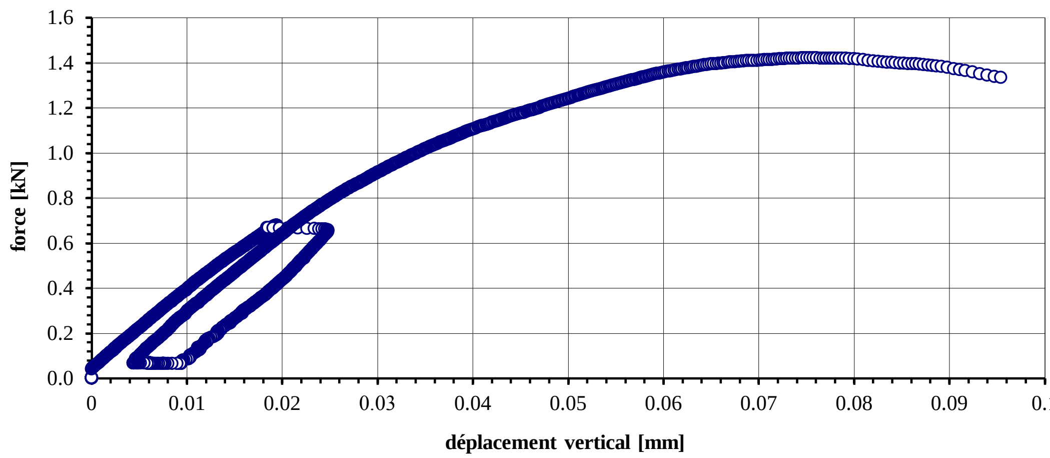
No sond.	Prof. [m]	Nature échantillon	Echantillon prélevé par	Date réception	Date essai
khd ML1 c	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	18.06.15

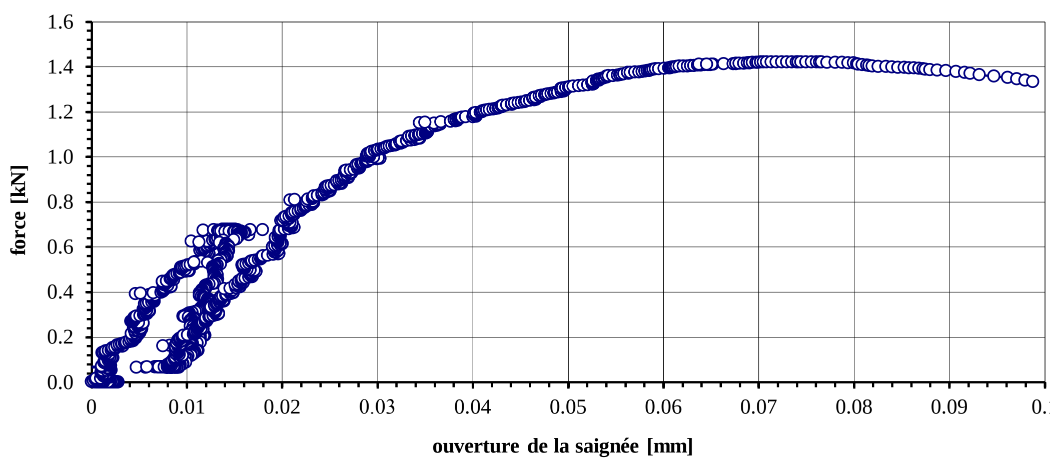
Mode conservation	Mode préparation éprouvette	Ingénieur responsable nom	Ingénieur responsable signature	Opérat.
NATUREL	CAROTTAGE + SCIAGE	F. SANDRONE		LG

Long. D [mm]	Diam. [mm]	ép. saignée t [mm]	a_0 [mm]	orientation schistosité/charge	KCB [MN/m$^{1.5}$]
220.0	56.0	1.7	8.3	PARALLELE	**1.32**

Amin=(1.835+(7.15*ao/Di)+(9.85*(ao/Di)^2))*Si/Di

KCB = Amin*Fmax/(Di^1.5)





Observations:

Ce protocole ne peut être reproduit partiellement et son contenu ne concerne que l'éprouvette testée

En outre, il fait partie d'une série d'essais, voir page "Rapport d'essais"

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ER.540 07/09

R0839_khd_ml1c_para-toughness.xls

Sample R0839-Kec-CS2-Perpendicular after

Sample R0839-Kec-CS3-Parallel after

Sample R0839-Kec-CS3-Perpendicular after

Sample R0839-Kt-RA1-Parallel after

Sample R0839-Kt-RA3-Parallel after

Sample R0839-Kd-ZT1-Perpendicular after

Sample R0839-Khd-ML1a-Parallel after

Sample R0839-Khd-ML1b-Parallel after

Sample R0839-Khd-ML1c-Parallel after

Appendix 4. Cracked Chevron Notched Brazilian Disk (CCNBD) Method Mode I Fracture Toughness Strength Test Results and Sample Photographs

This appendix contains the stress-strain results and before and after photographs for each of the 25 cracked chevron notched Brazilian disk fracture toughness tests performed on the Yosemite Valley rock samples. All test results are reported in English.

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

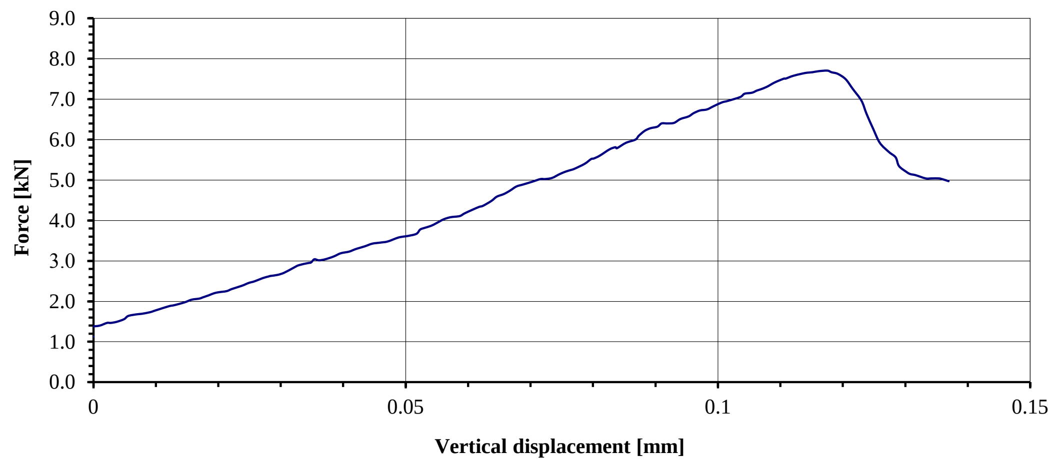
No sample	Study title	Client – Name	Client – Address
R0839-CCNBD-Kec-CS2-Para	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

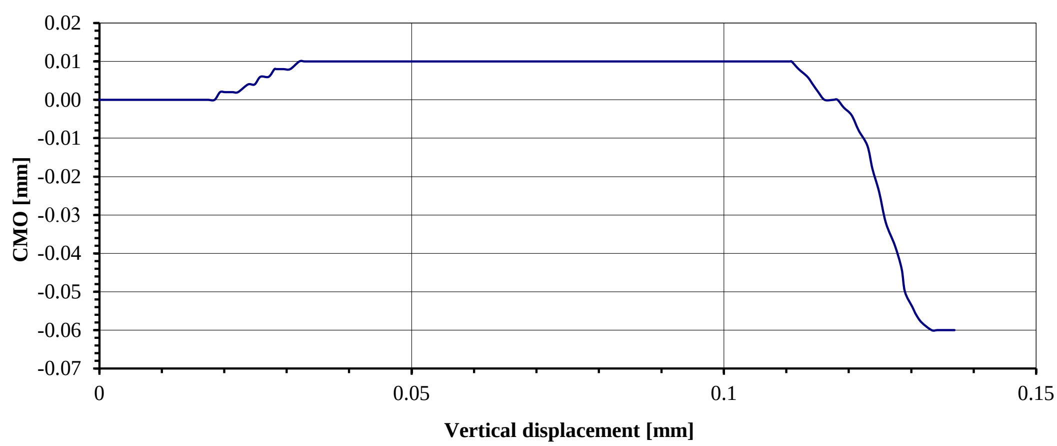
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	14.11.14

Type of storage	orientation schistosity/load	Engineer responsible – Name	Engineer responsible – Signature	Operator
NATUREL	PARALLEL	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.4	13.0	23.8	0.7848	7.706	**0.995**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

This protocol cannot be partially reproduced and its contents concerns only the tested specimen

Besides, it is a part of a test series, cf " test report " page

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ISRM 1995

R0839-Kec-CS2-Para-statique.xls

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

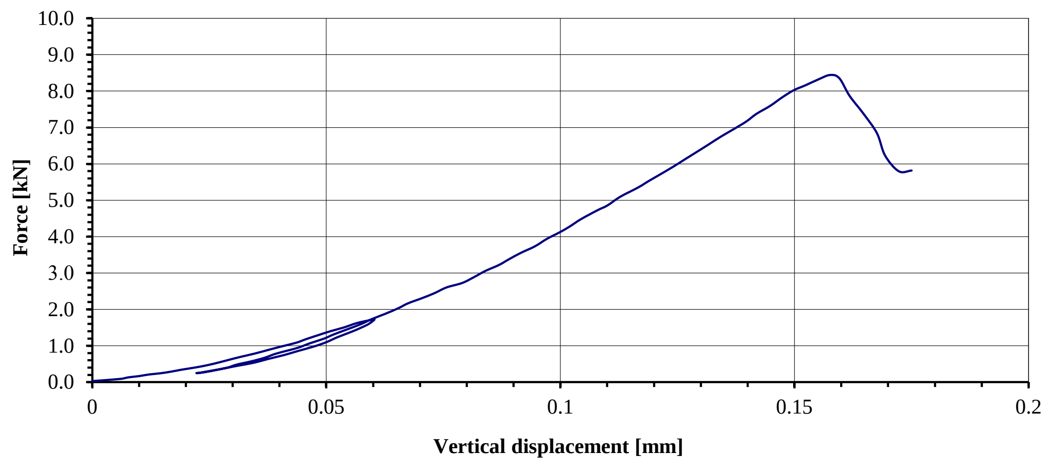
Performed according to Standard ISRM (1995)

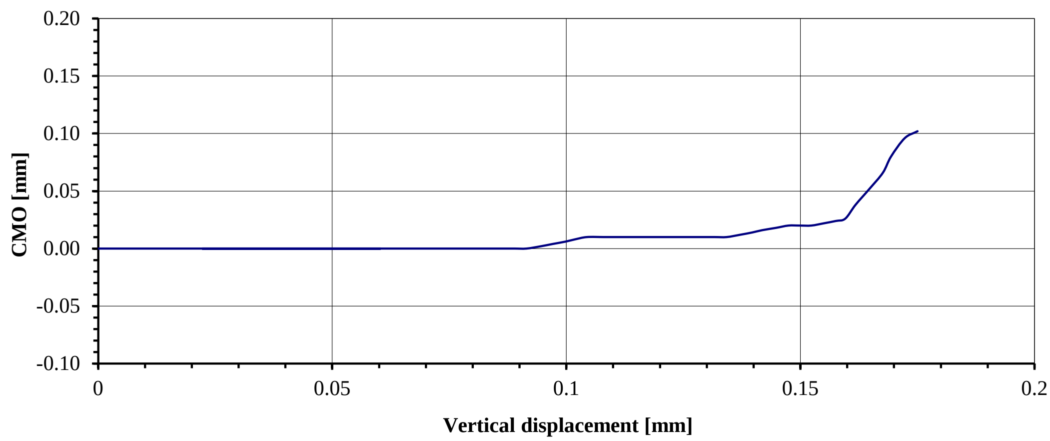
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Kec-CS2-Per		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date	
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	19.05.15	
Type of storage		orientation schistosity/load	Engineer responsible		Operator	
			Name	Signature		
NATUREL		PERPENDICULAR	F. Sandrone		LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
81.0	30.9	15.2	24.3	0.8103	8.442	**1.100**

$R = \frac{D}{2}$ $\alpha_1 = \frac{a_1}{R}$ $\alpha_0 = \frac{a_0}{R}$ $\alpha_B = \frac{B}{R}$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

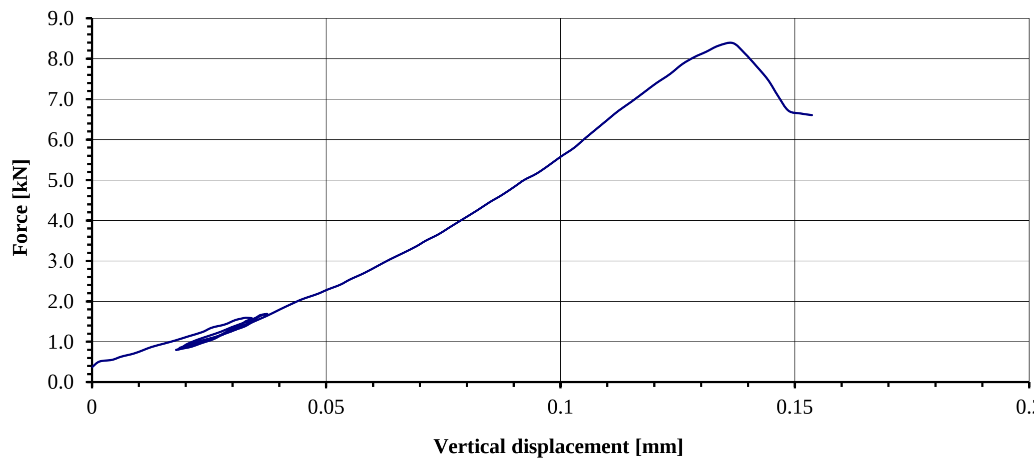
No sample	Study title	Client	
		Name	Address
R0839-CCNBD-Kec-CS3-Para	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

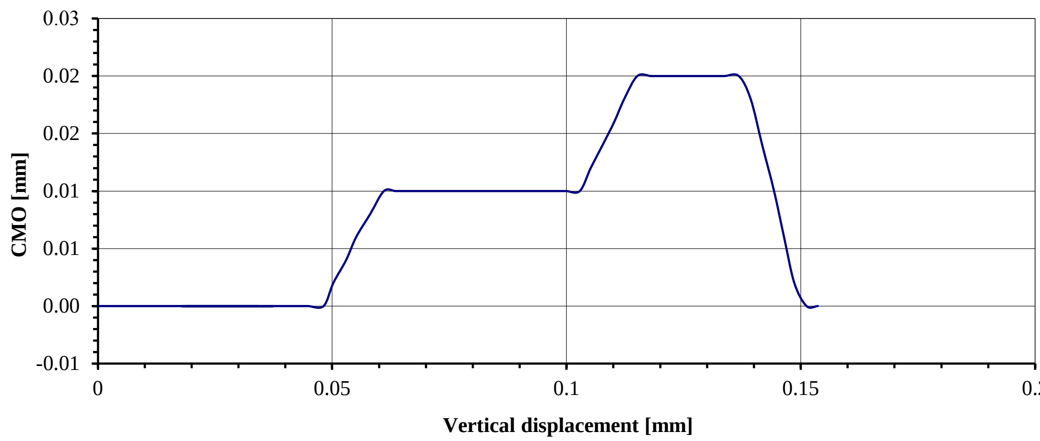
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	09.04.15

Type of storage	orientation schistosity/load	Engineer responsible		Operator
		Name	Signature	
NATUREL	PARALLEL	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
79.9	30.8	12.3	23.8	0.7789	8.388	**1.061**

$R = \frac{D}{2}$ $\alpha_1 = \frac{a_1}{R}$ $\alpha_0 = \frac{a_0}{R}$ $\alpha_B = \frac{B}{R}$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

LMS-LMR 75 ANS 1935-2010

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

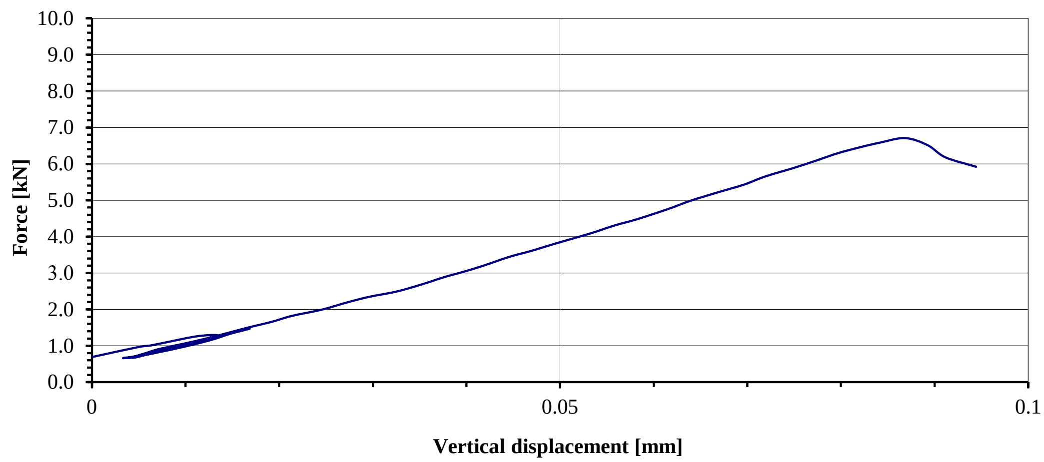
No sample		Study title	Client	
			Name	Address
R0839-CCNBD-Kec-CS3-Per		CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

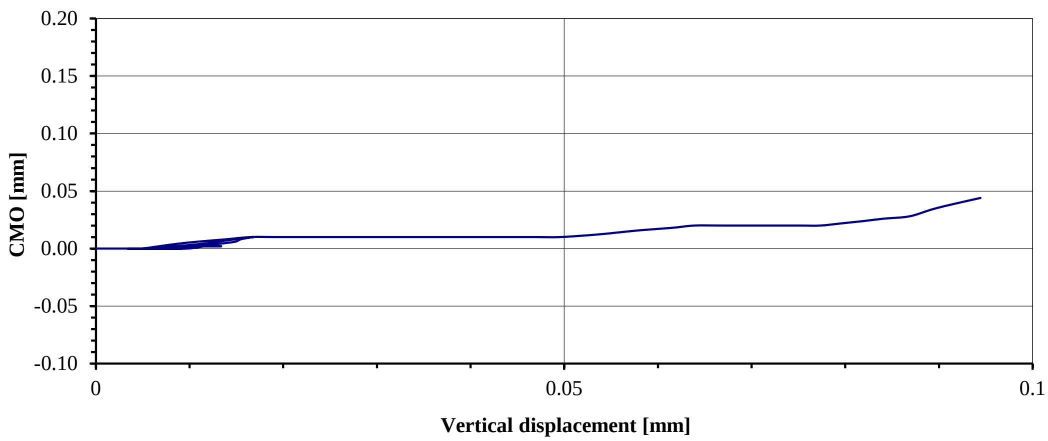
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kec	-	EL CAPITAN GRANITE	COMMETTANT	08.07.14	09.04.15

Type of storage	orientation schistosity/load	Engineer responsible		Operator
		Name	Signature	
NATUREL	PERPENDICULAR	F. Sandrone		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.9	12.5	23.8	0.7781	6.708	**0.845**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

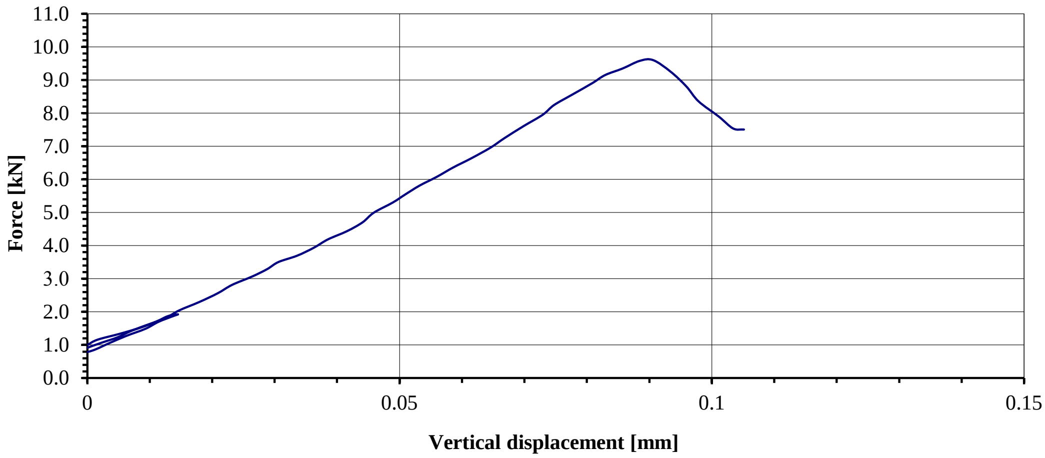
Performed according to Standard ISRM (1995)

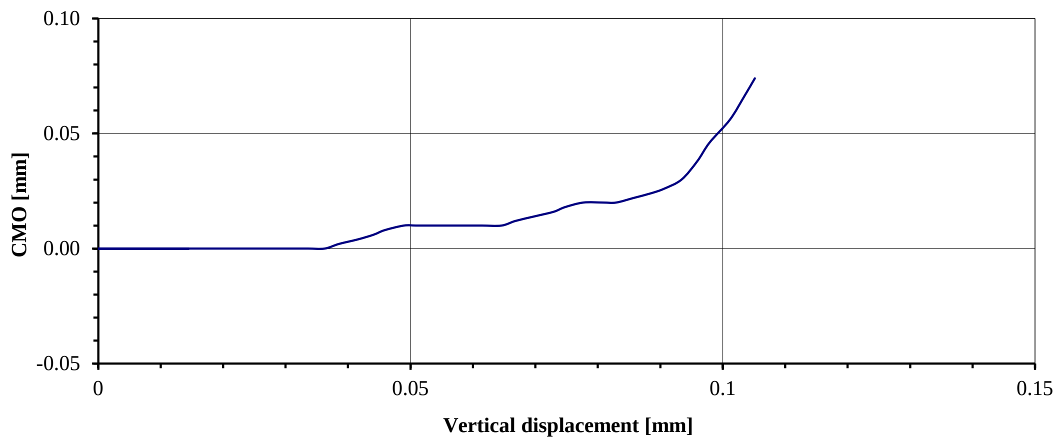
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Kgb-NT1-Para		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date	
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	19.05.15	
Type of storage		orientation schistosity/load	Engineer responsible		Operator	
			Name	Signature		
NATUREL		PARRALEL	F. SANDRONE	[signature]	LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
79.5	30.2	13.8	24.2	0.8131	9.602	**1.297**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

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Besides, it is a part of a test series, cf " test report " page

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SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

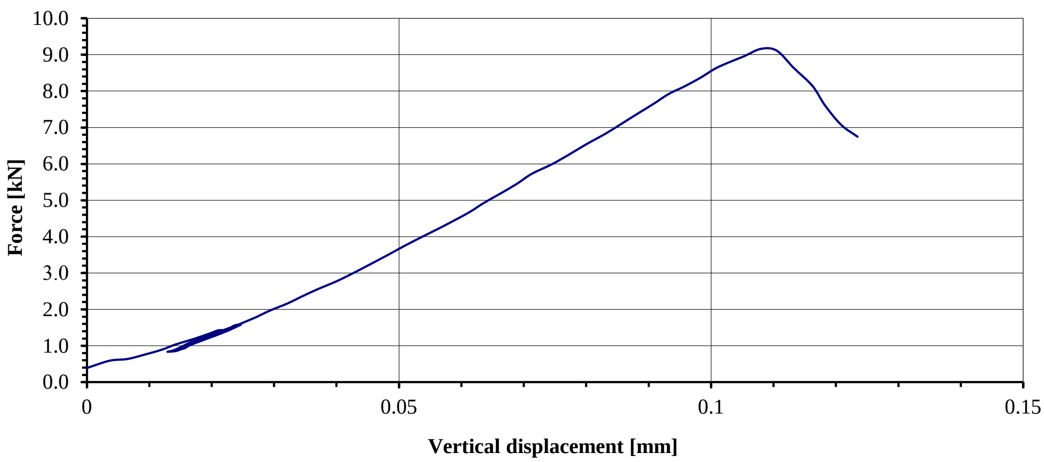
No sample	Study title	Client: Name	Client: Address
R0839-CCNBD-Kgb-NT1-Per	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

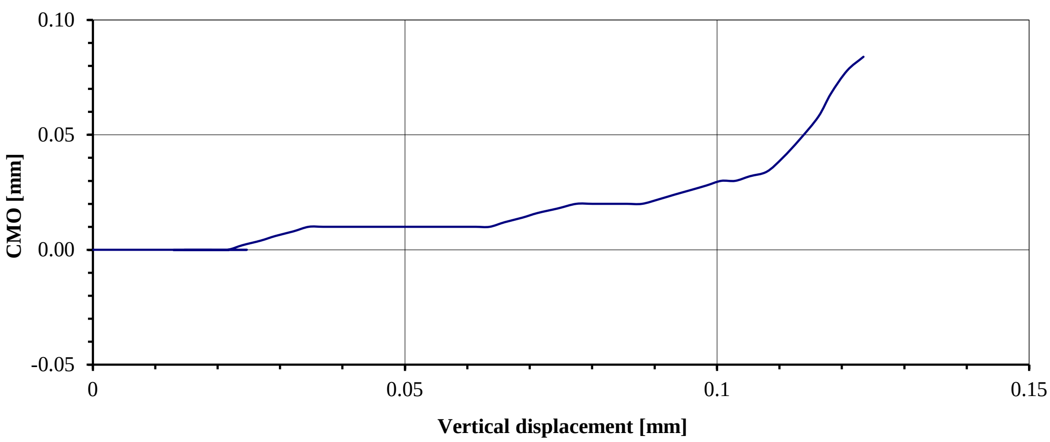
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	09.04.15

Type of storage	orientation schistosity/load	Engineer responsible: Name	Engineer responsible: Signature	Operator
NATUREL	PERPENDICULAR	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.9	13.3	24.0	0.7928	9.160	**1.175**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

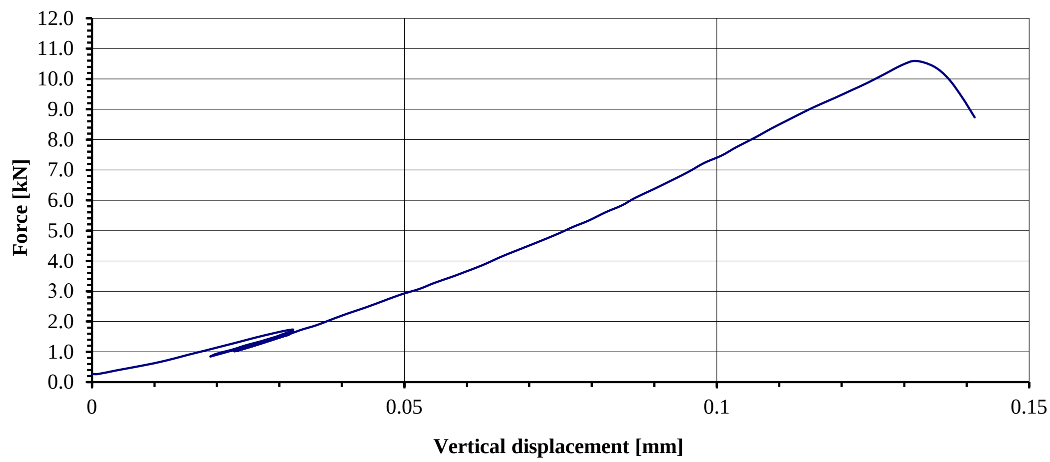
Performed according to Standard ISRM (1995)

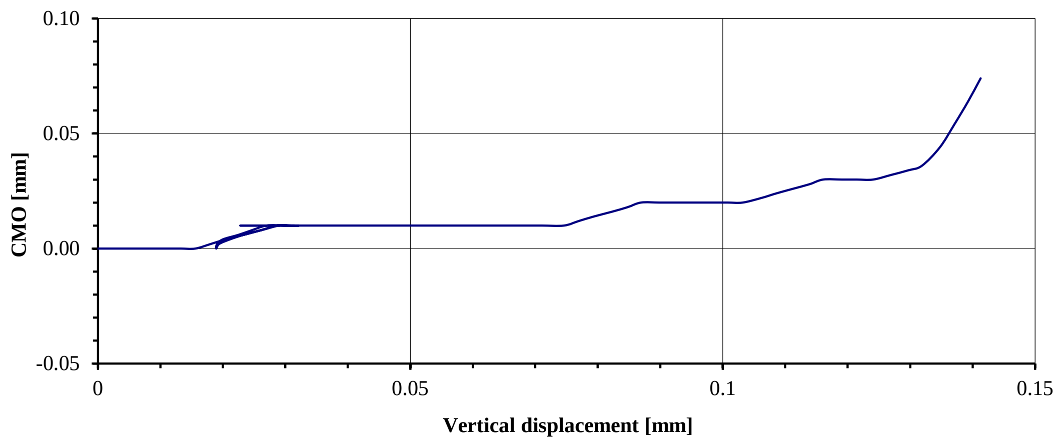
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client		
			Name		Address
R0839-CCNBD-Kgb-NT2-Per		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA
Borehole	**Depth [m]**	**Rock type**	**Sample taken by**	**Delivery date**	**Test date**
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	09.04.15
Type of storage		**orientation schistosity/load**	**Engineer responsible**		**Operator**
			Name	**Signature**	
NATUREL		PERPENDICULAR	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.2	30.9	13.3	24.2	0.7976	10.594	**1.366**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

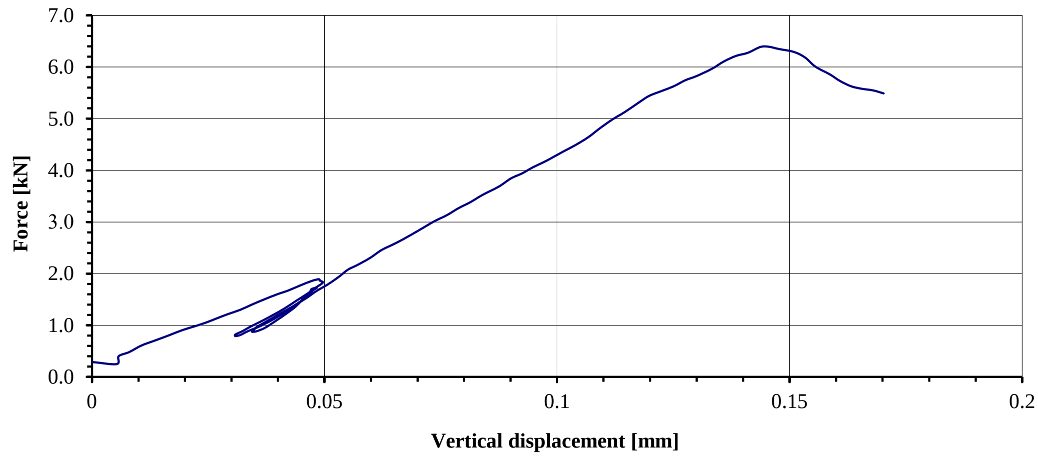
Performed according to Standard ISRM (1995)

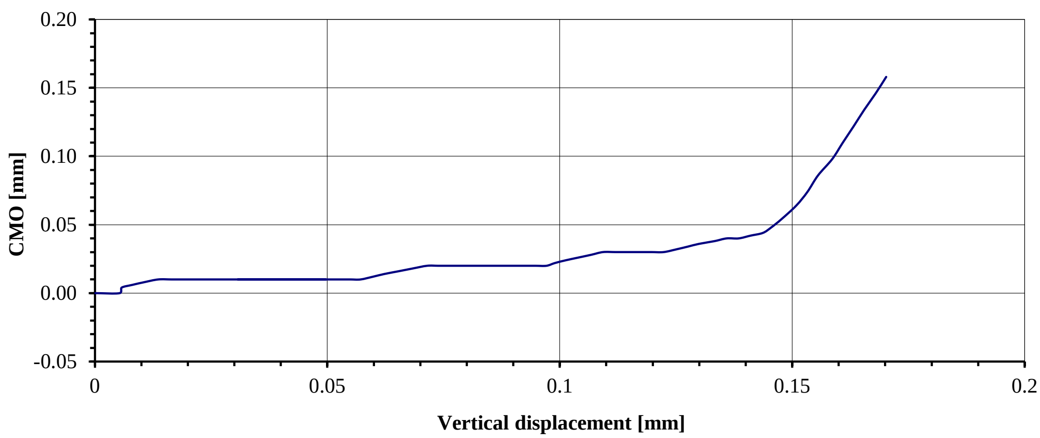
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client		
			Name		Address
R0839-CCNBD-Kgb-NT3-Per		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kgb	-	TONALITE OF THE GREY BANDS	COMMETTANT	08.07.14	09.04.15
Type of storage		orientation schistosity/load	Engineer responsible		Operator
			Name	Signature	
NATUREL		PERPENDICULAR	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	31.2	13.2	24.2	0.8002	6.394	**0.820**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





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SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

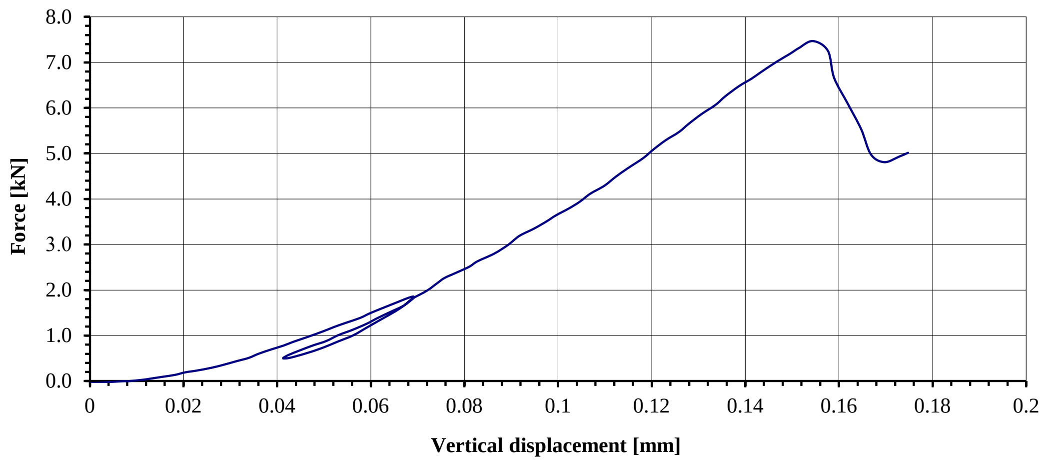
No sample	Study title	Client	
		Name	Address
R0839-CCNBD-Kt-RA1-Para	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

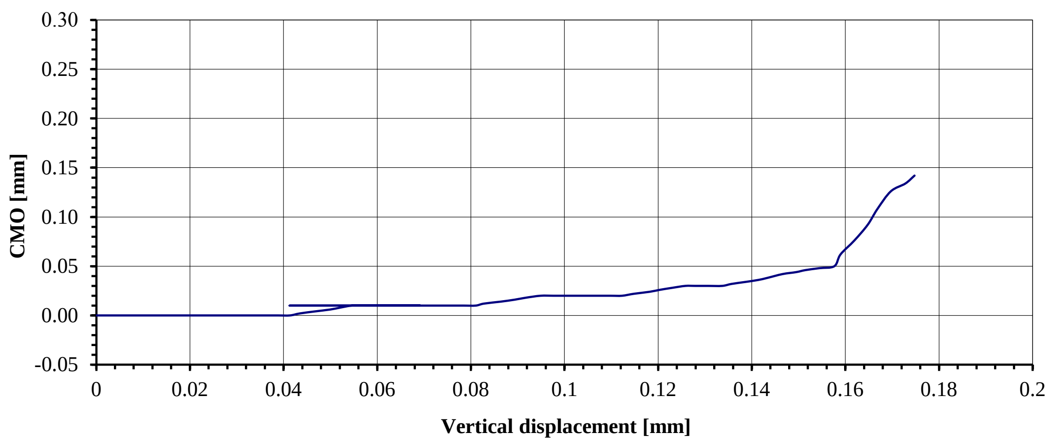
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	19.05.15

Type of storage	orientation schistosity/load	Engineer responsible		Operator
		Name	Signature	
NATUREL	PARALLEL	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
79.5	30.7	14.3	24.3	0.8181	7.468	**0.998**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

LMS-LMR 75 ANS 1935-2010

FRACTURE TOUGHNESS - Mode I CCNBD

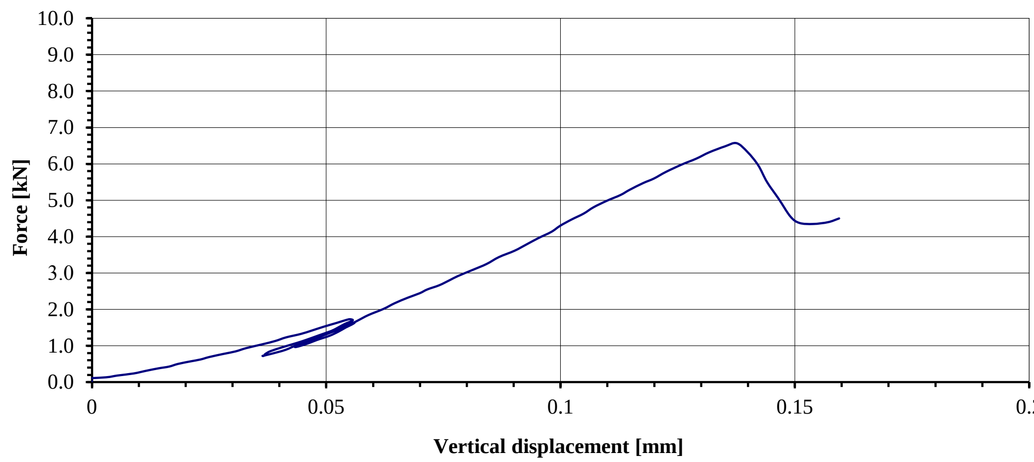
Performed according to Standard ISRM (1995)

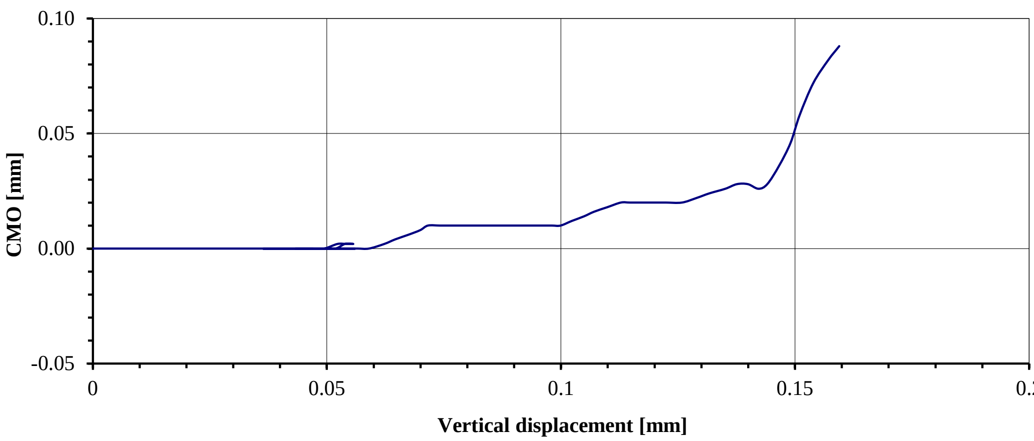
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Kt-RA1-Per		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date	
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	09.04.15	
Type of storage		orientation schistosity/load	Engineer responsible		Operator	
			Name	Signature		
NATUREL		PERPENDICULAR	F. Sandrone	[signature]	LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.7	11.4	23.8	0.7701	6.568	**0.824**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





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SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

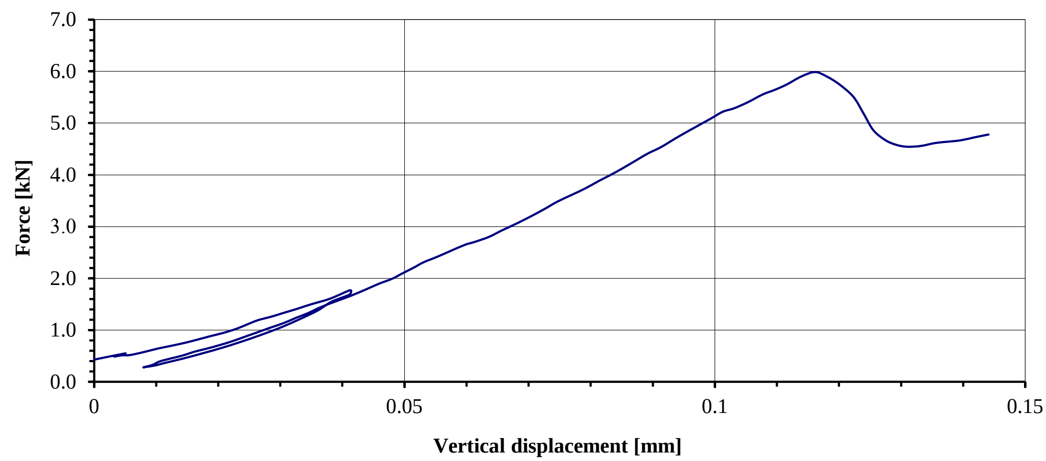
No sample	Study title	Client: Name	Client: Address
R0839-CCNBD-Kt-RA2-Para	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

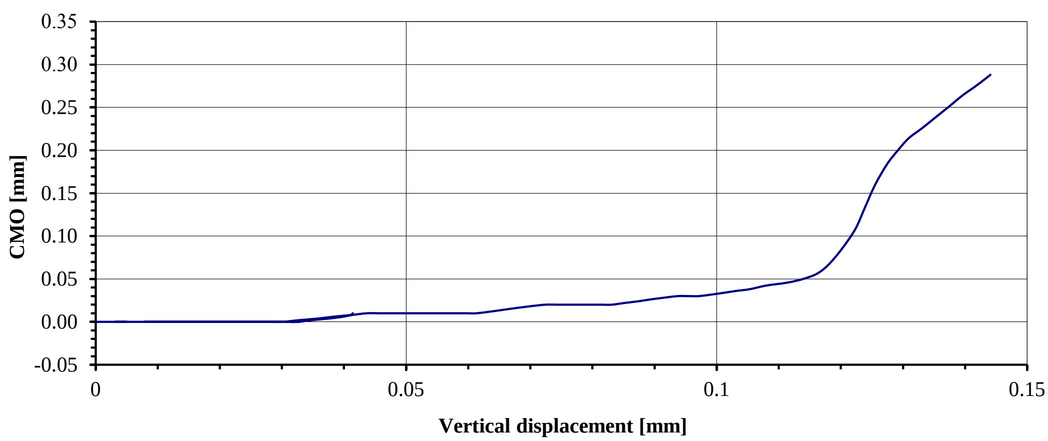
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14	07.05.15

Type of storage	orientation schistosity/load	Engineer responsible: Name	Engineer responsible: Signature	Operator
NATUREL	PARALLEL	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
79.9	30.1	13.7	24.3	0.8120	5.988	**0.808**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

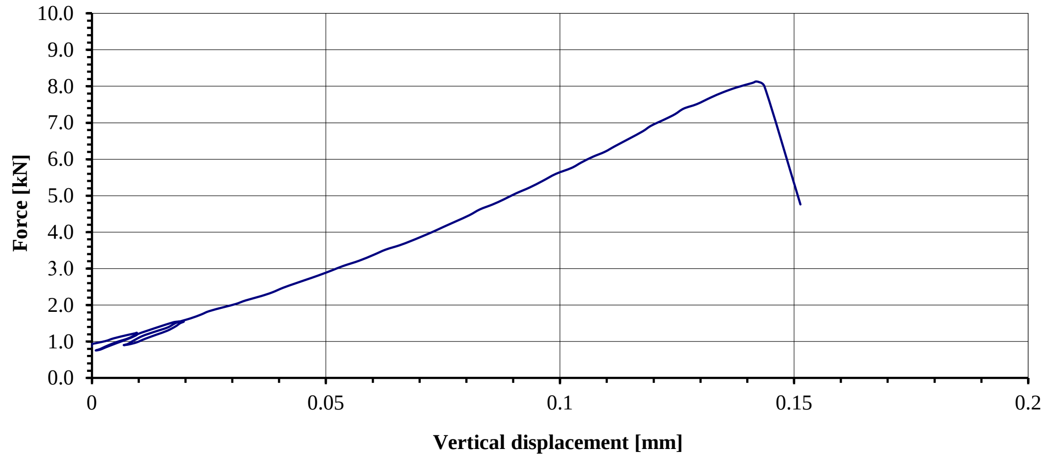
Performed according to Standard ISRM (1995)

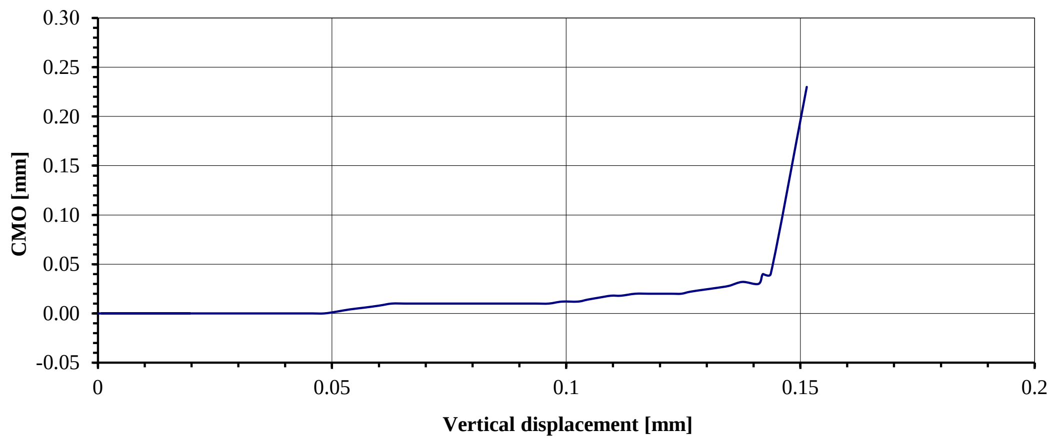
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Kt-RA2-Per		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date		Test date
Kt	-	TAFT GRANITE	COMMETTANT	08.07.14		09.04.15
Type of storage		orientation schistosity/load	Engineer responsible			Operator
			Name	Signature		
NATUREL		PERPENDICULAR	F. Sandrone			LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.9	10.1	24.6	0.7906	8.130	**1.040**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

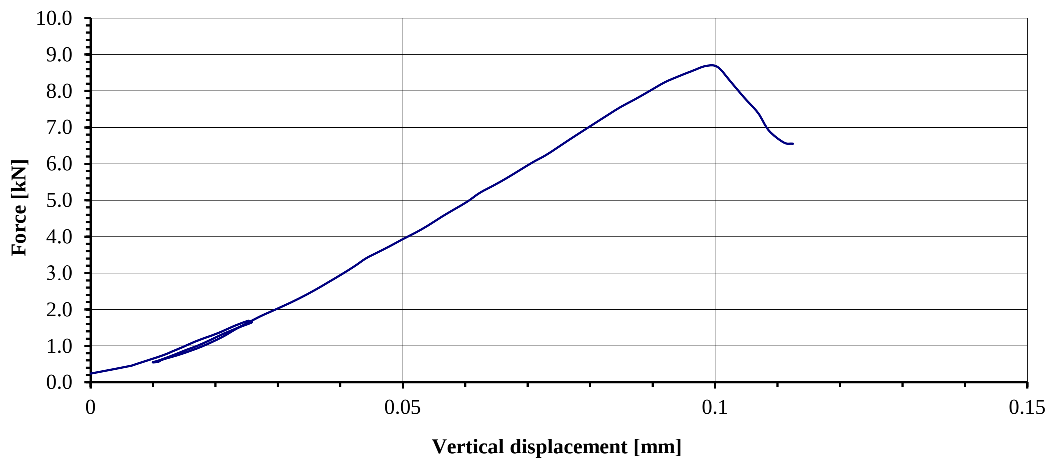
Performed according to Standard ISRM (1995)

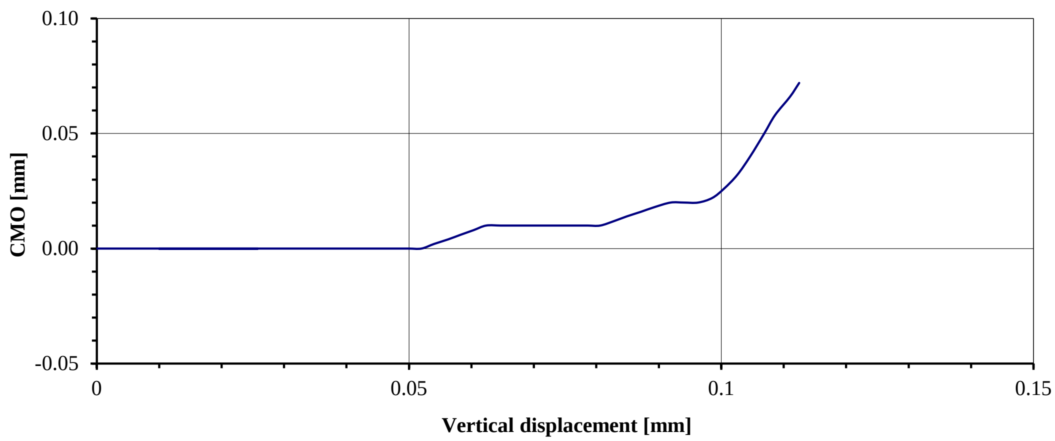
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client		
			Name		Address
R0839-CCNBD-Kd-ZT1-Para		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	07.05.15
Type of storage		orientation schistosity/load	Engineer responsible		Operator
			Name	Signature	
NATUREL		PARALLEL	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.4	13.5	24.0	0.7962	8.686	**1.138**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

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SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

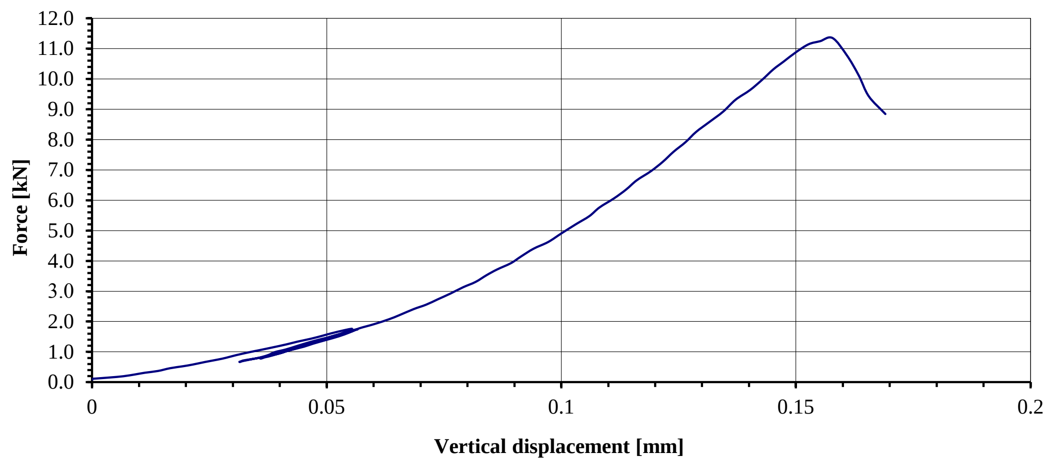
No sample	Study title	Client	
		Name	Address
R0839-CCNBD-Kd-ZT1-Per	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

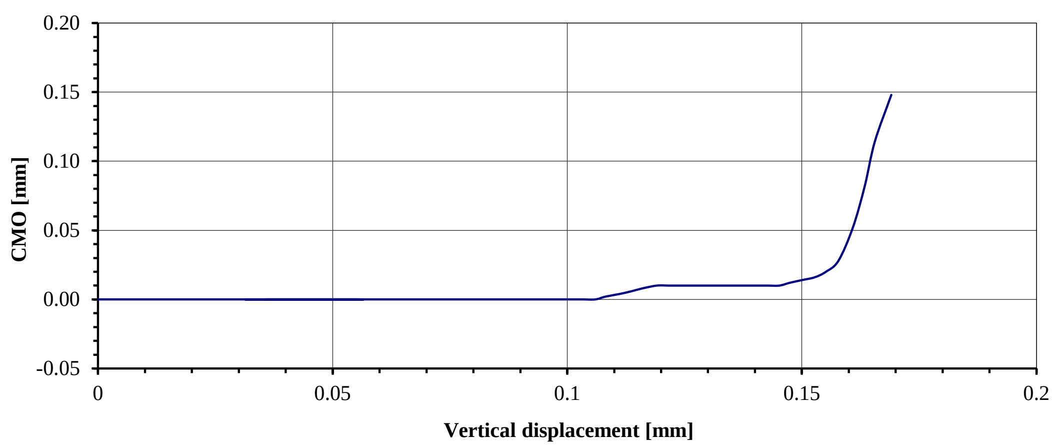
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	09.04.15

Type of storage	orientation schistosity/load	Engineer responsible		Operator
		Name	Signature	
NATUREL	PERPENDICULAR	F. Sandrone		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.1	12.5	24.1	0.7948	11.35	**1.498**

$R = \frac{D}{2}$ $\alpha_1 = \frac{a_1}{R}$ $\alpha_0 = \frac{a_0}{R}$ $\alpha_B = \frac{B}{R}$





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SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

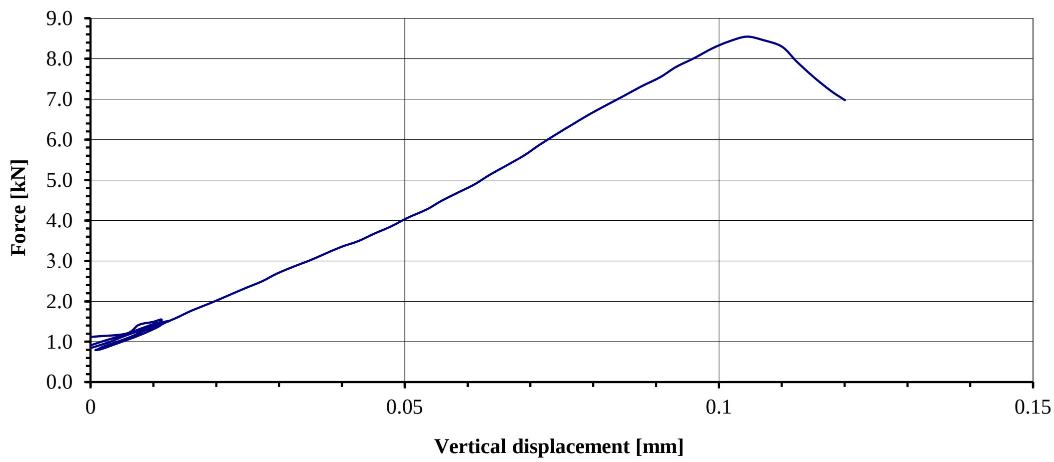
Performed according to Standard ISRM (1995)

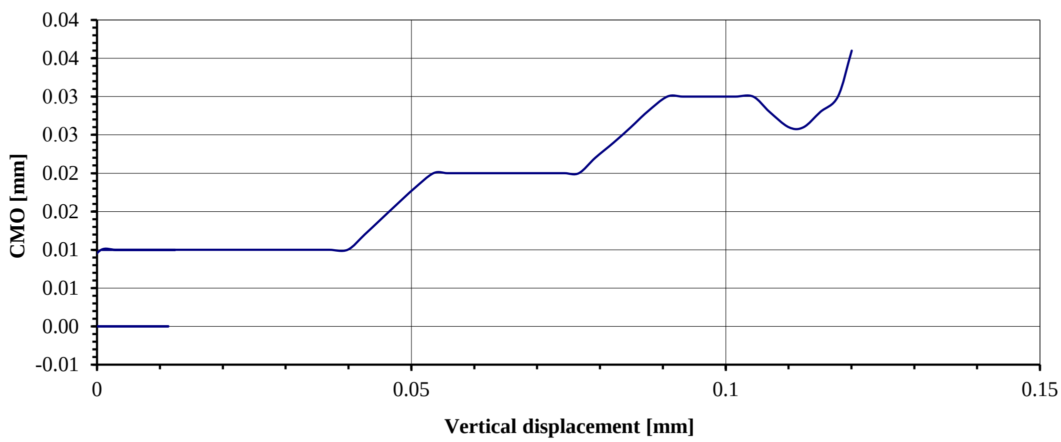
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Kd-ZT2-Para		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date	
Kd	-	DIORITE OF NORTH AMERICAN WALL	COMMETTANT	08.07.14	09.04.15	
Type of storage		orientation schistosity/load	Engineer responsible		Operator	
			Name	Signature		
NATUREL		PARALLEL	F. SANDRONE		LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.2	30.5	13.5	24.2	0.7975	10.024	**1.309**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

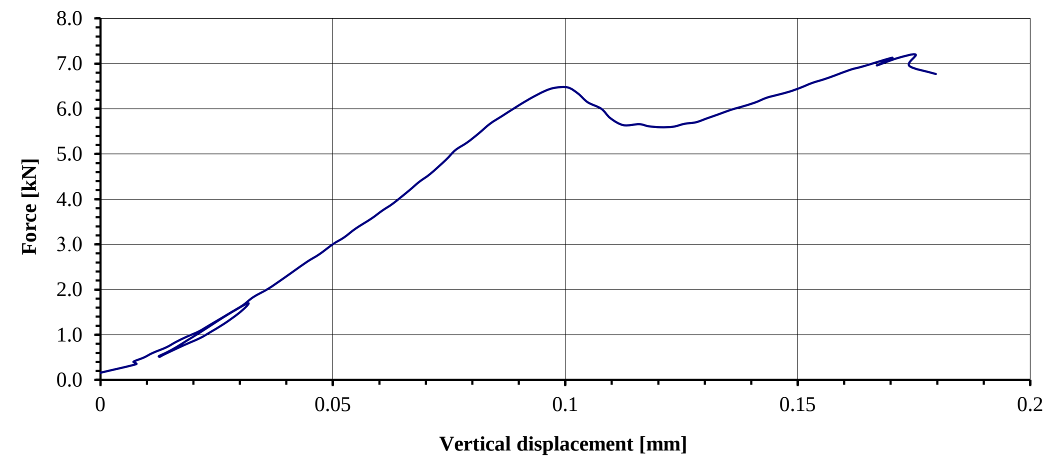
Performed according to Standard ISRM (1995)

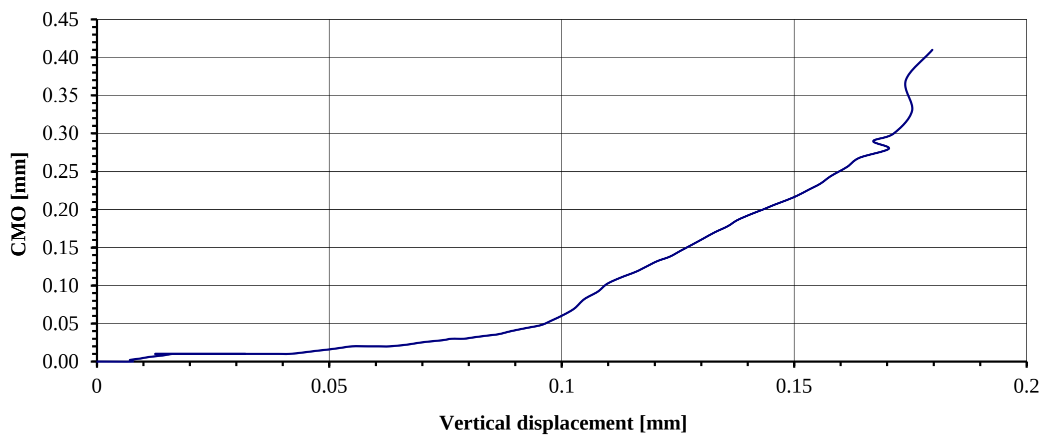
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Ks-IC1-Para		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	**Depth [m]**	**Rock type**	**Sample taken by**	**Delivery date**	**Test date**	
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	19.05.15	
Type of storage		**orientation schistosity/load**	**Engineer responsible**		**Operator**	
			Name	**Signature**		
NATUREL		PARALLEL	F. Sandrone		LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	31.0	13.5	24.2	0.8002	7.200	**0.929**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





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SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

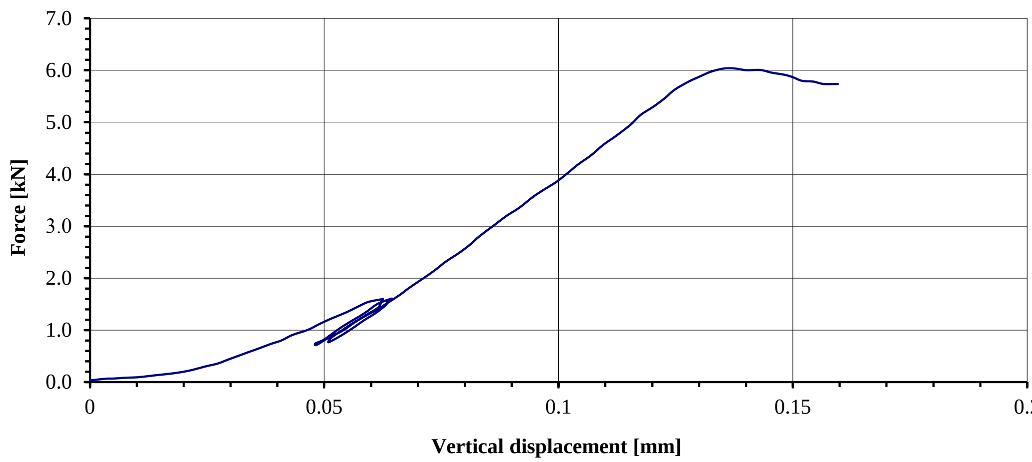
No sample	Study title	Client	
		Name	Address
R0839-CCNBD-Ks-IC1-Per	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

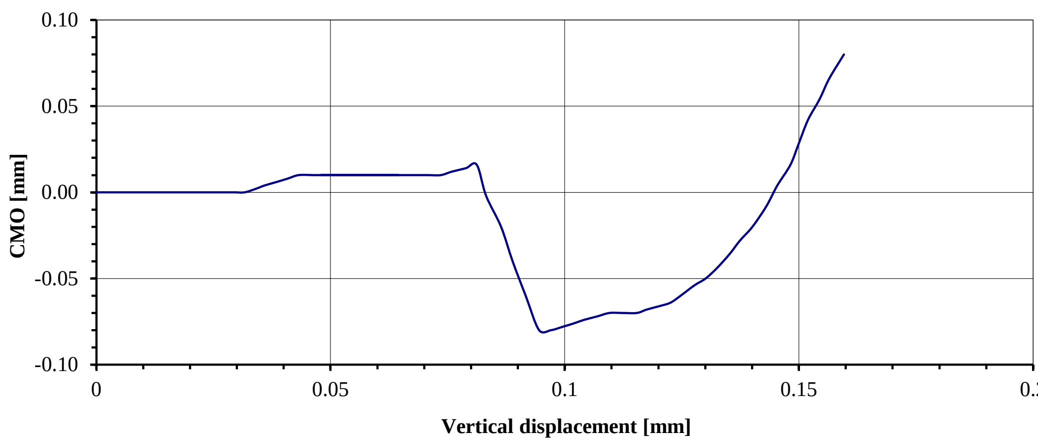
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	09.04.15

Type of storage	orientation schistosity/load	Engineer responsible		Operator
		Name	Signature	
NATUREL	PERPENDICULAR	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
79.9	30.7	12.9	24.3	0.7968	7.714	**1.002**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

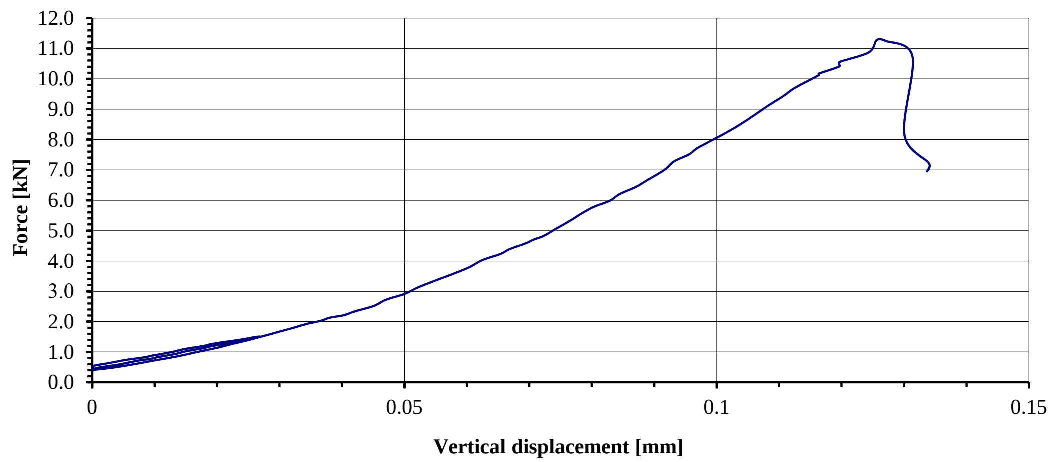
Performed according to Standard ISRM (1995)

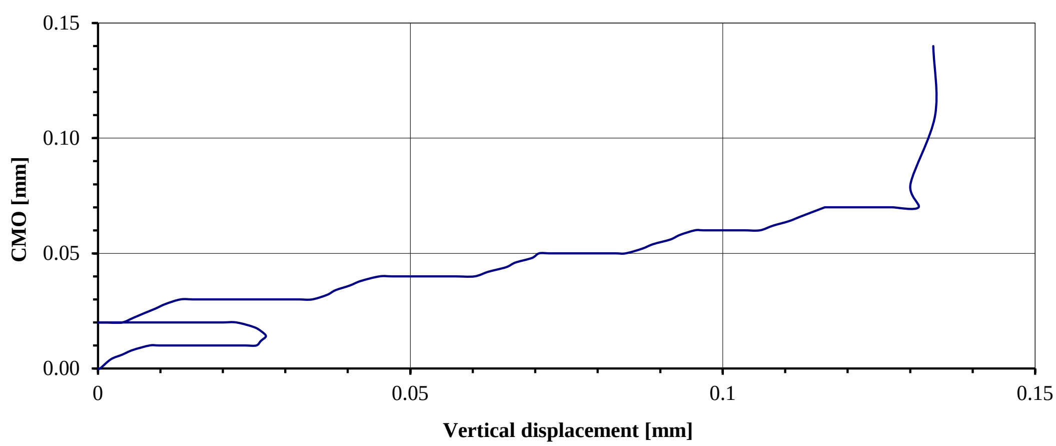
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Ks-IC2-Para		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date	
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	05.05.15	
Type of storage		orientation schistosity/load	Engineer responsible		Operator	
			Name	Signature		
NATUREL		PARALLEL	F. Sandrone		LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	31.6	12.8	24.3	0.7963	11.280	**1.421**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

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Besides, it is a part of a test series, cf " test report " page

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

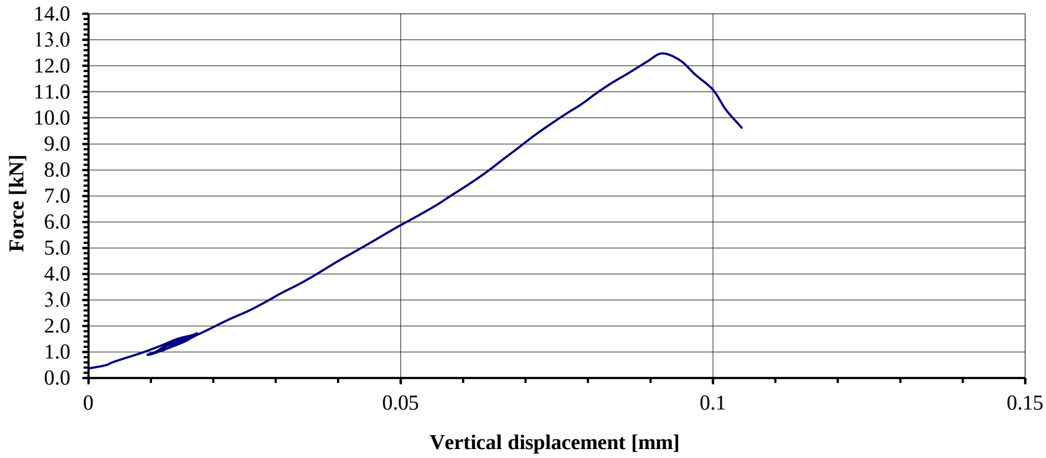
No sample	Study title	Client	
		Name	Address
R0839-CCNBD-Ks-IC2-Per	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

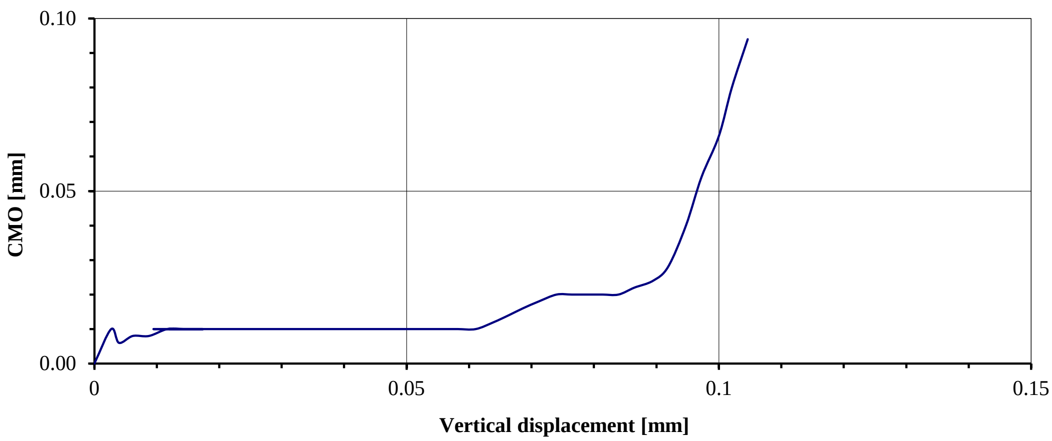
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Ks	-	SENTINEL GRANODIORITE	COMMETTANT	08.07.14	09.04.15

Type of storage	orientation schistosity/load	Engineer responsible		Operator
		Name	Signature	
NATUREL	PERPENDICULAR	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.9	12.9	24.2	0.7923	12.478	**1.600**

$$R=\frac{D}{2} \qquad \alpha_1=\frac{a_1}{R} \qquad \alpha_0=\frac{a_0}{R} \qquad \alpha_B=\frac{B}{R}$$





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R0839-KS-IC2-Per-statique.xls

SOIL AND ROCK MECHANICS LABORATORIES

LMS-LMR 75 ANS 1935-2010

FRACTURE TOUGHNESS - Mode I CCNBD

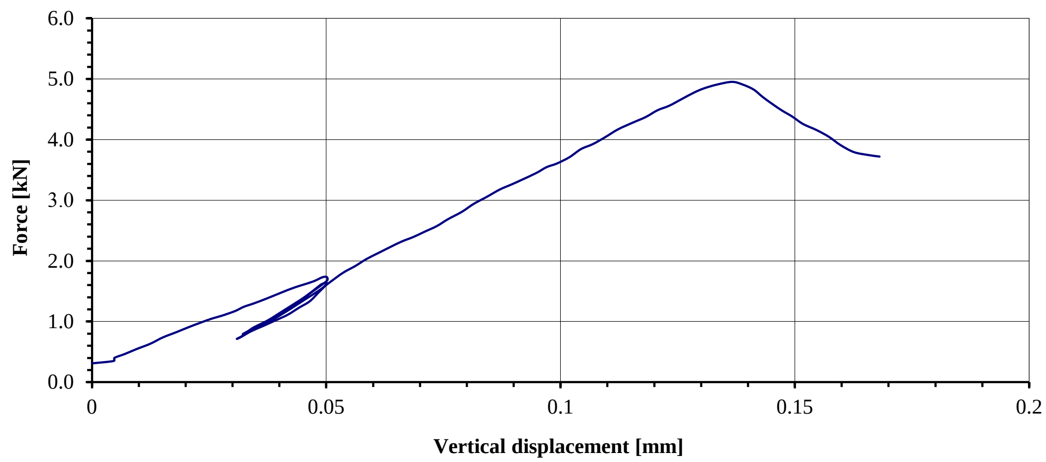
Performed according to Standard ISRM (1995)

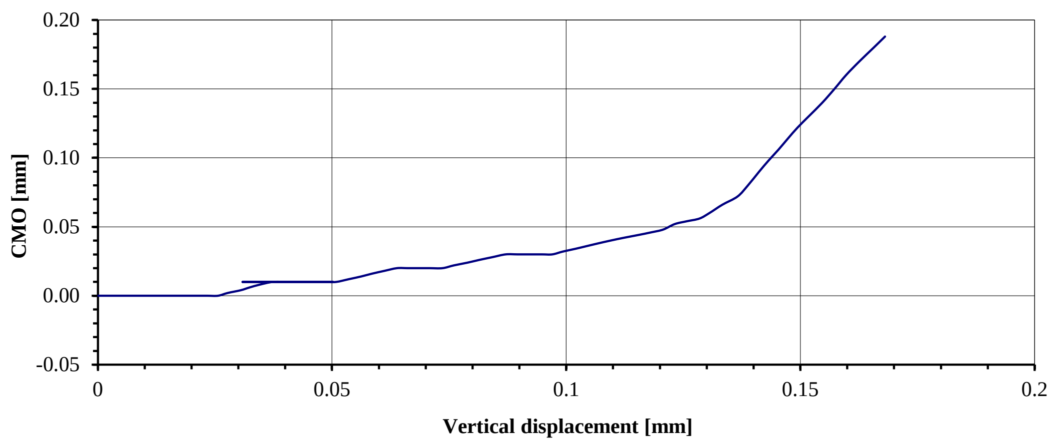
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Khd-RP1-Para		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	**Depth [m]**	**Rock type**	**Sample taken by**	**Delivery date**	**Test date**	
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	09.04.15	
Type of storage		**orientation schistosity/load**	**Engineer responsible**		**Operator**	
			Name	**Signature**		
NATUREL		PARALLEL	F. SANDRONE		LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
79.9	30.1	11.5	23.7	0.7745	4.952	**0.637**

$R = \frac{D}{2}$ $\alpha_1 = \frac{a_1}{R}$ $\alpha_0 = \frac{a_0}{R}$ $\alpha_B = \frac{B}{R}$





Notes

This protocol cannot be partially reproduced and its contents concerns only the tested specimen Page 1/1
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R0839-Khd-RP1-Para-statique.xls

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

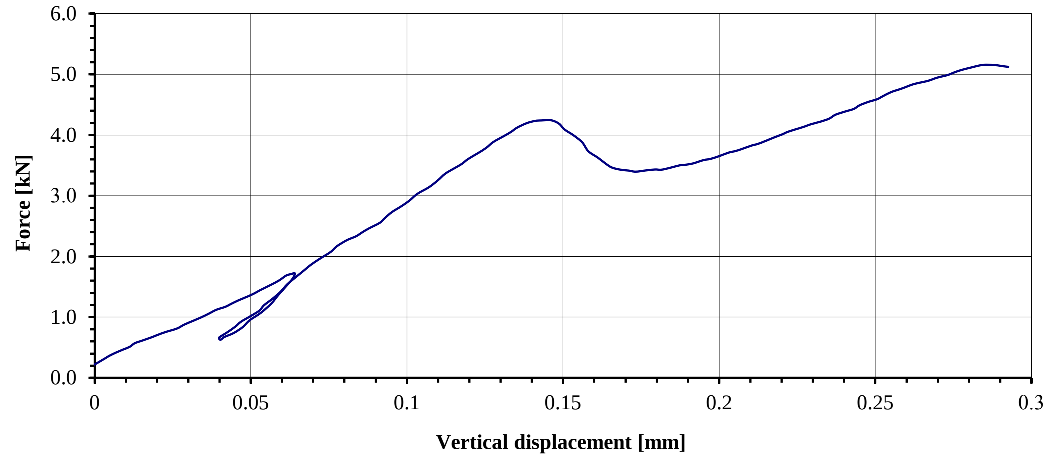
No sample	Study title	Client	
		Name	Address
R0839-CCNBD-Khd-RP1-Per	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

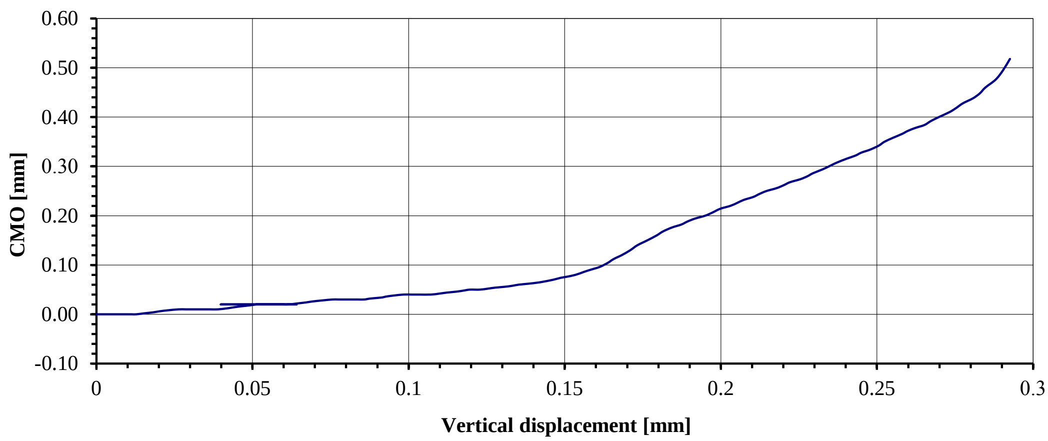
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	19.05.15

Type of storage	orientation schistosity/load	Engineer responsible		Operator
		Name	Signature	
NATUREL	PERPENDICULAR	F. Sandrone		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
81.0	30.0	14.6	24.3	0.8086	5.156	**0.691**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

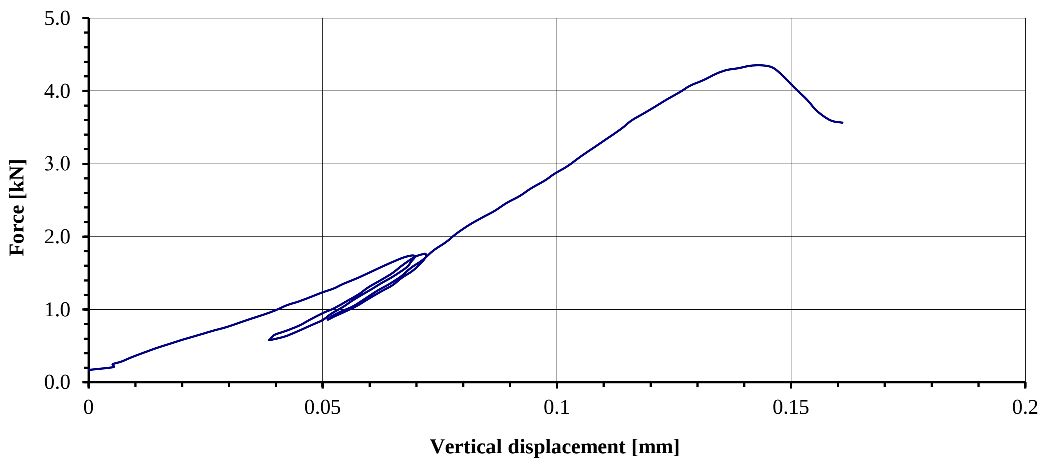
Performed according to Standard ISRM (1995)

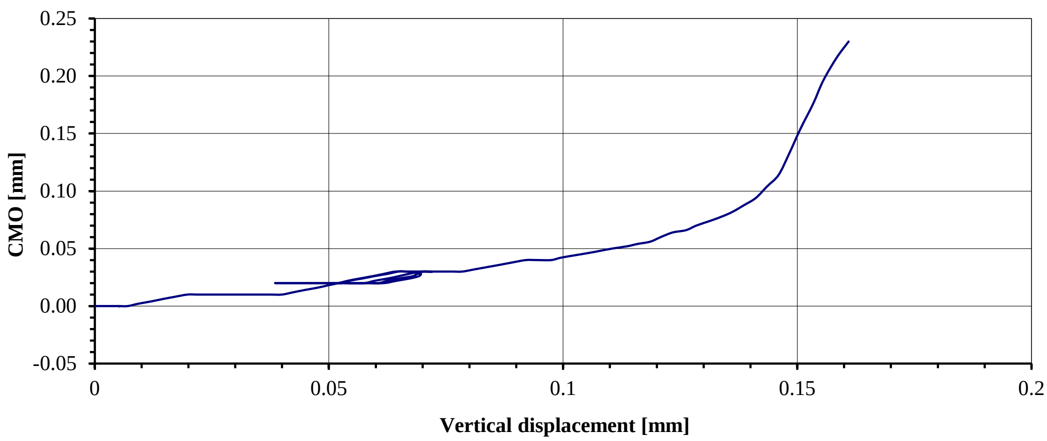
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client		
			Name		Address
R0839-CCNBD-Khd-RP4-Par		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	09.04.15
Type of storage		orientation schistosity/load	Engineer responsible		Operator
			Name	Signature	
NATUREL		PARALLEL	F. SANDRONE		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	31.1	12.0	24.3	0.7919	5.050	**0.643**

$R = \frac{D}{2}$ $\alpha_1 = \frac{a_1}{R}$ $\alpha_0 = \frac{a_0}{R}$ $\alpha_B = \frac{B}{R}$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

Performed according to Standard ISRM (1995)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

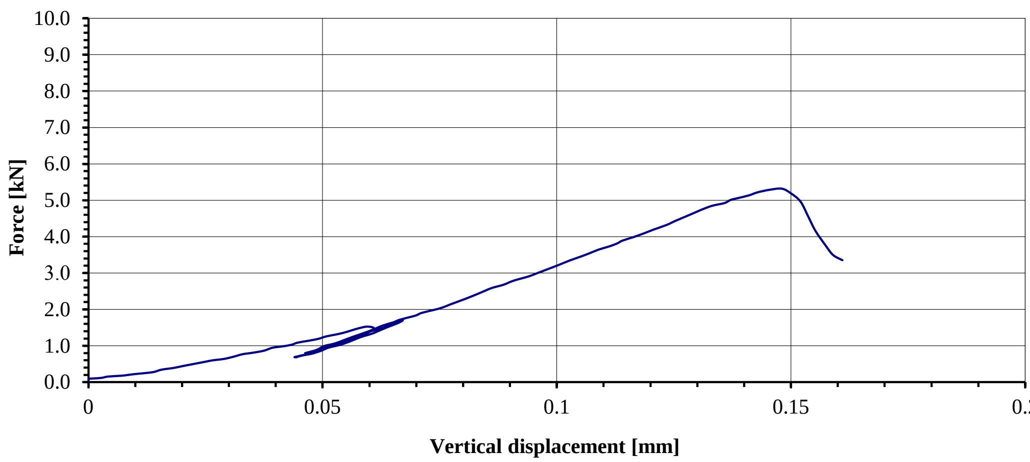
No sample	Study title	Client: Name	Client: Address
R0839-CCNBD-Khd-RP4-Per	CCNBD-STATIC UNIL/USGS	UNIL-USGS	USA

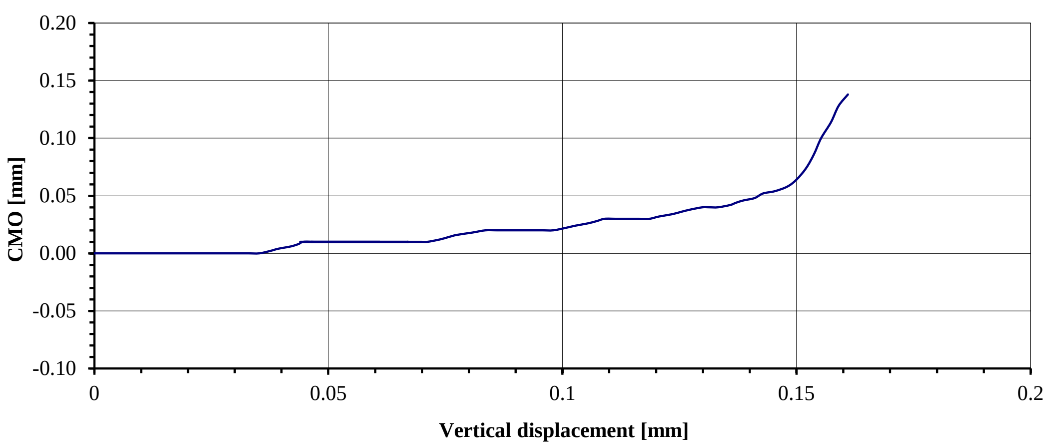
Borehole	Depth [m]	Rock type	Sample taken by	Delivery date	Test date
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	09.04.15

Type of storage	orientation schistosity/load	Engineer responsible: Name	Engineer responsible: Signature	Operator
NATUREL	PERPENDICULAR	F. Sandrone		LG

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.9	12.4	24.0	0.7849	5.318	**0.675**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

SOIL AND ROCK MECHANICS LABORATORIES

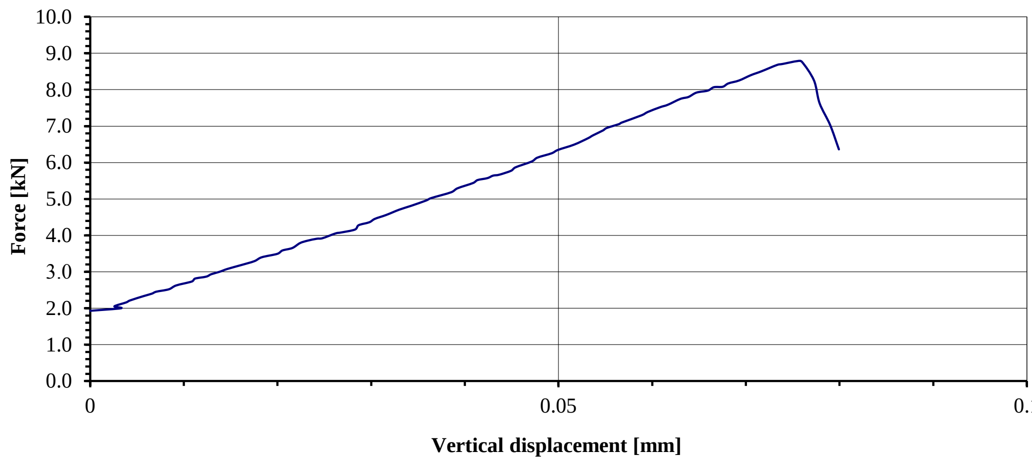
FRACTURE TOUGHNESS - Mode I CCNBD

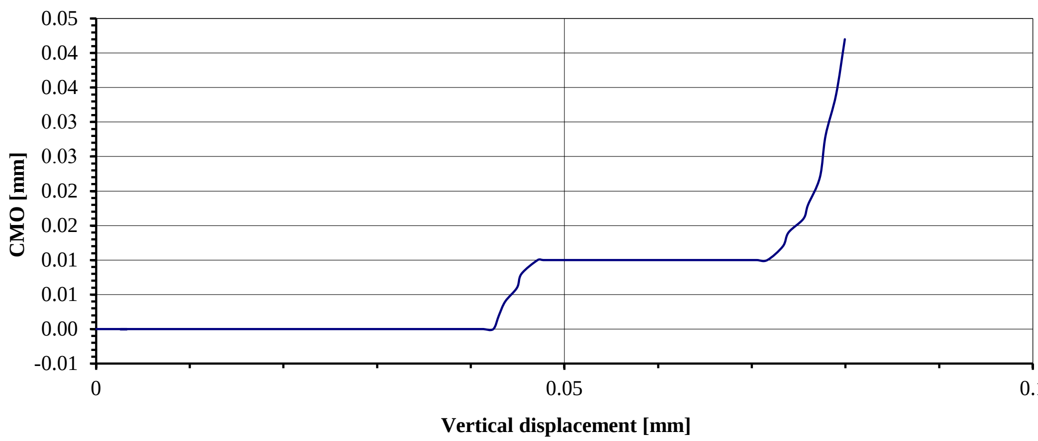
Performed according to Standard ISRM (1995)

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Khd-ML1-Para		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	**Depth [m]**	**Rock type**	**Sample taken by**	**Delivery date**	**Test date**	
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	13.11.14	
Type of storage		**orientation schistosity/load**	**Engineer responsible**		**Operator**	
			Name	**Signature**		
NATUREL		PARALLEL	F. SANDRONE		LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	31.1	12.0	24.3	0.7919	8.786	**1.119**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





Notes

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SOIL AND ROCK MECHANICS LABORATORIES

FRACTURE TOUGHNESS - Mode I CCNBD

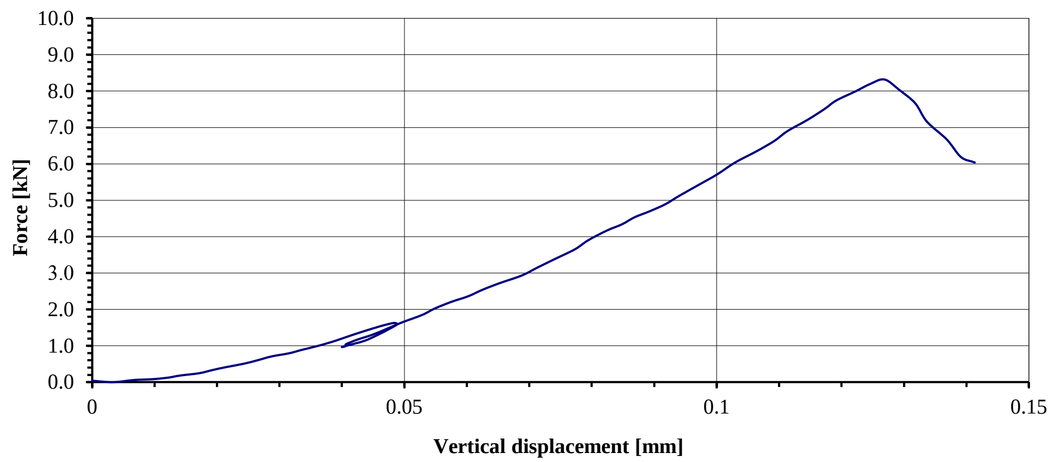
Performed according to Standard ISRM (1995)

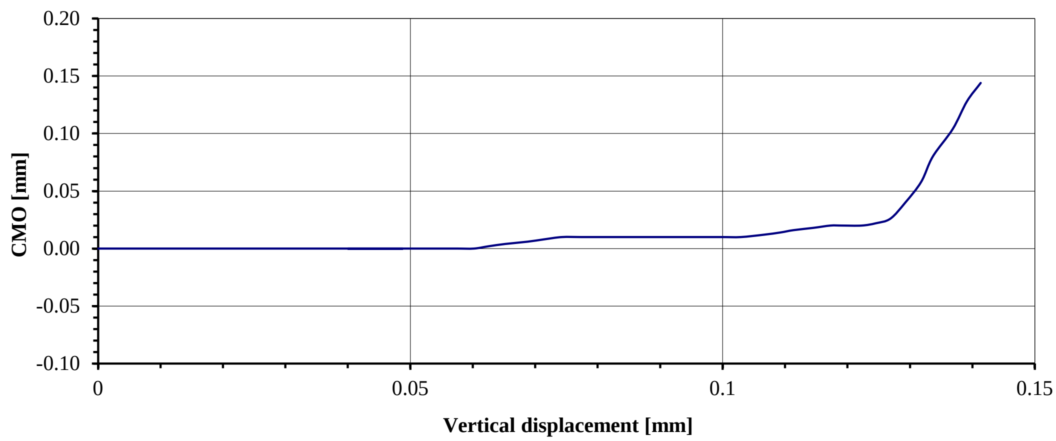
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

No sample		Study title	Client			
			Name		Address	
R0839-CCNBD-Khd-ML1-Per		CCNBD-STATIC UNIL/USGS	UNIL-USGS		USA	
Borehole	**Depth [m]**	**Rock type**	**Sample taken by**	**Delivery date**	**Test date**	
Khd	-	HALF DOME GRANODIORITE	COMMETTANT	08.07.14	09.04.15	
Type of storage		**orientation schistosity/load**	**Engineer responsible**		**Operator**	
			Name	**Signature**		
NATUREL		PERPENDICULAR	F. Sandrone		LG	

Diameter D [mm]	Thickness B [mm]	Initial crack lenght a_0 [mm]	Final crack lenght a_1 [mm]	Y^*_{min} [-]	P_{max} [MN]	K_{IC} [MN/m$^{1.5}$]
80.0	30.8	13.4	24.0	0.7928	8.318	**1.071**

$$R = \frac{D}{2} \qquad \alpha_1 = \frac{a_1}{R} \qquad \alpha_0 = \frac{a_0}{R} \qquad \alpha_B = \frac{B}{R}$$





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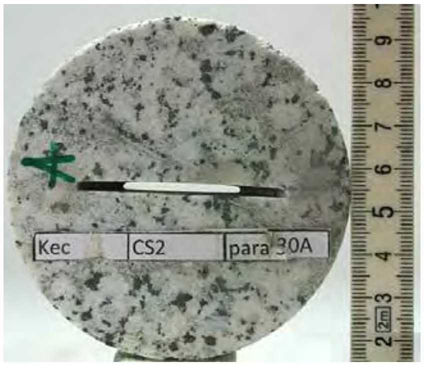
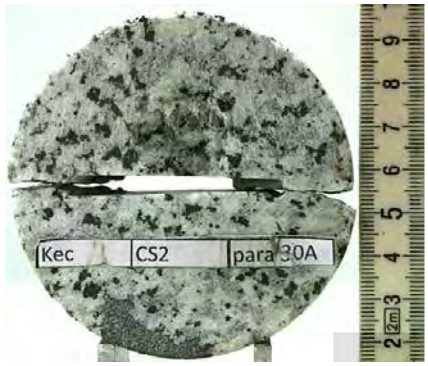


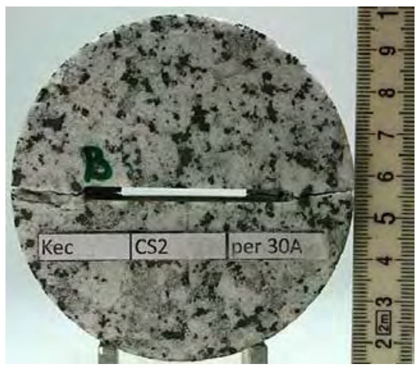
Sample R0839-Kec-CS2-Parallel_A before



Sample R0839-Kec-CS2-Parallel_A after

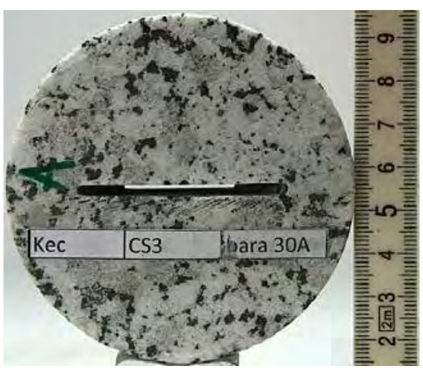
Sample R0839-Kec-CS2-Parallel_A notch

Sample R0839-Kec-CS2-Perpendicular_A before

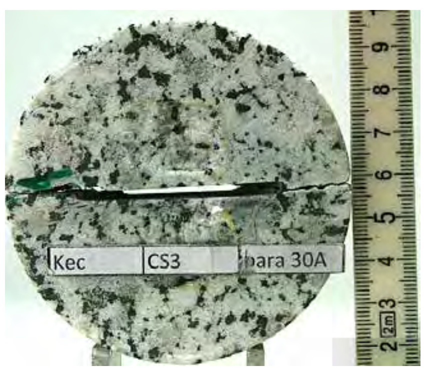


Sample R0839-Kec-CS2-Perpendicular_A after

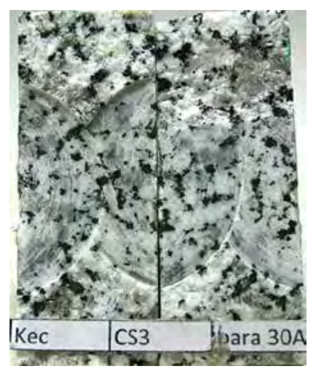
Sample R0839-Kec-CS2-Perpendicular_A notch



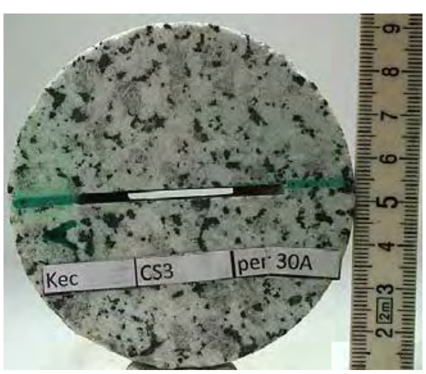
Sample R0839-Kec-CS3-Parallel_A before



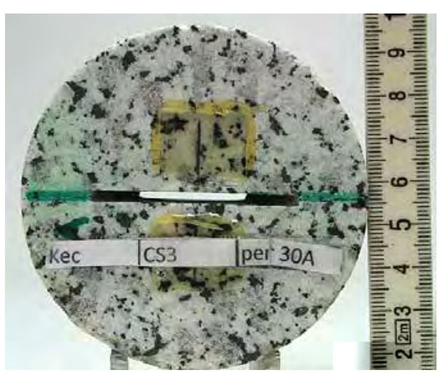
Sample R0839-Kec-CS3-Parallel_A after



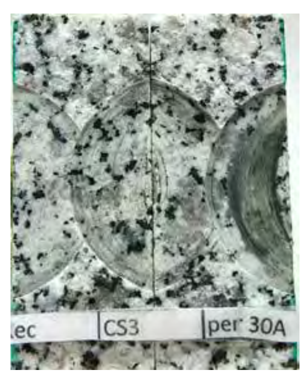
Sample R0839-Kec-CS3-Parallel_A notch



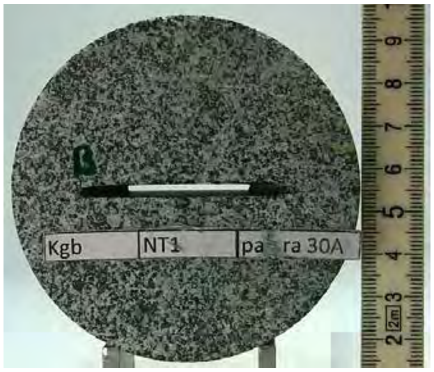
Sample R0839-Kec-CS3-Perpendicular_A before



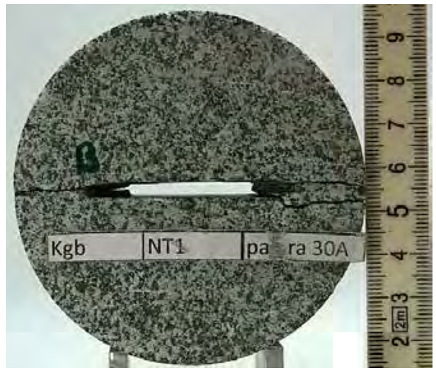
Sample R0839-Kec-CS3-Perpendicular_A after



Sample R0839-Kec-CS3-Perpendicular_A notch

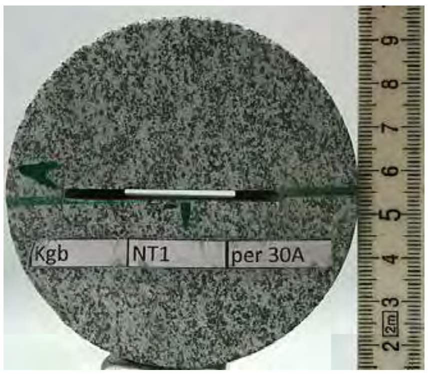


Sample R0839-Kgb-NT1-Parallel_A before

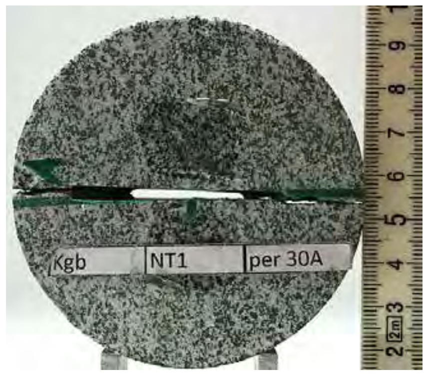


Sample R0839-Kgb-NT1-Parallel_A after

Sample R0839-Kgb-NT1-Parallel_A notch

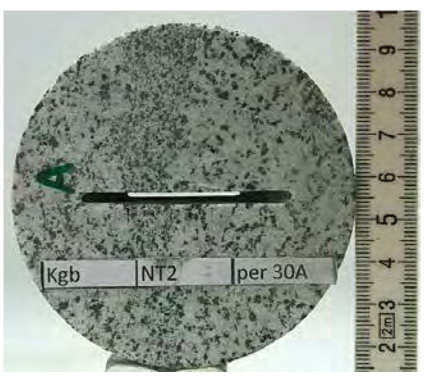


Sample R0839-Kgb-NT1-Perpendicular_A before

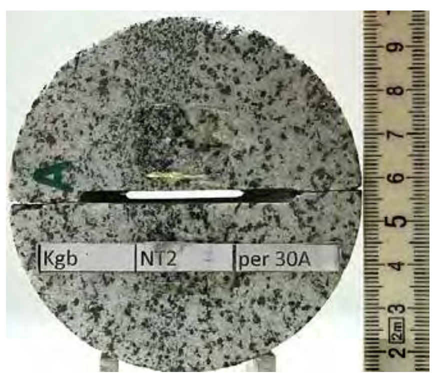


Sample R0839-Kgb-NT1-Perpendicular_A after

Sample R0839-Kgb-NT1-Perpendicular_A notch

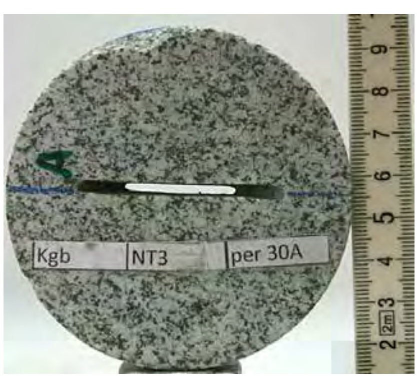


Sample R0839-Kgb-NT2-Perpendicular_A before

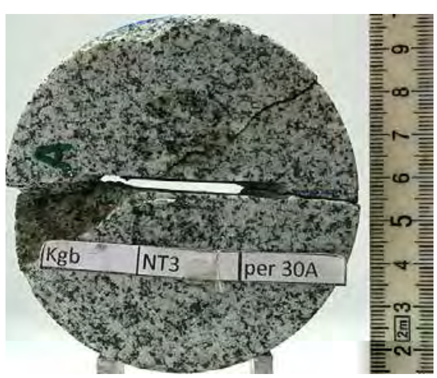


Sample R0839-Kgb-NT2-Perpendicular_A after

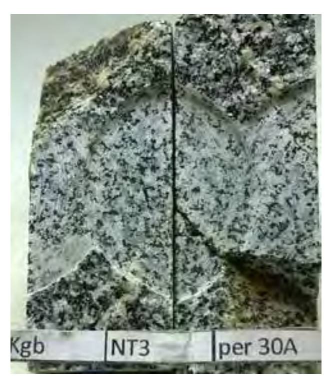
Sample R0839-Kgb-NT2-Perpendicular_A notch



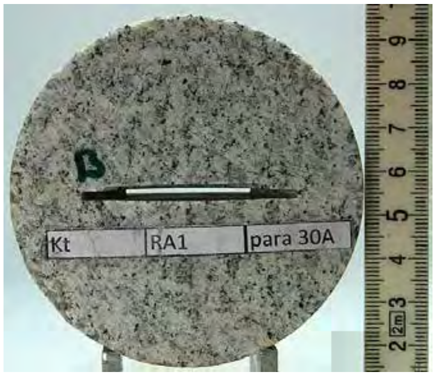
Sample R0839-Kgb-NT3-Perpendicular_A before



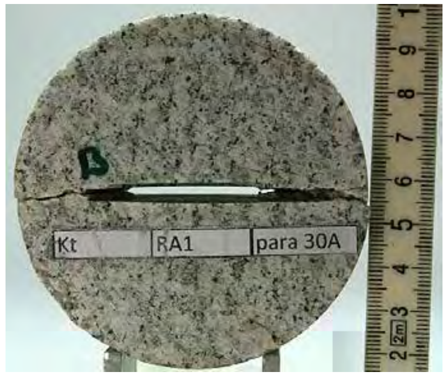
Sample R0839-Kgb-NT3-Perpendicular_A after



Sample R0839-Kgb-NT3-Perpendicular_A notch

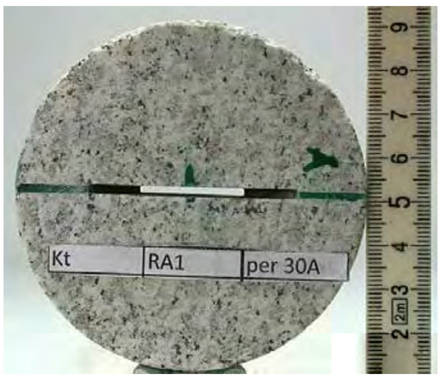


Sample R0839-Kt-RA1-Parallel_A before

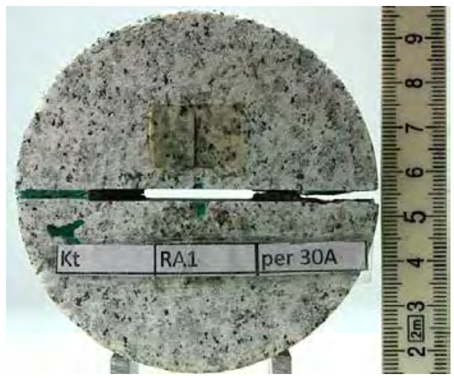


Sample R0839-Kt-RA1-Parallel_A after

Sample R0839-Kt-RA1-Parallel_A notch

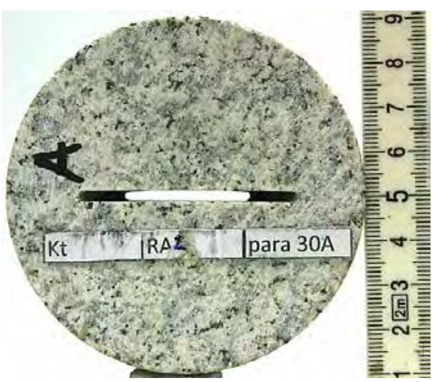


Sample R0839-Kt-RA1-Perpendicular_A before



Sample R0839-Kt-RA1-Perpendicular_A after

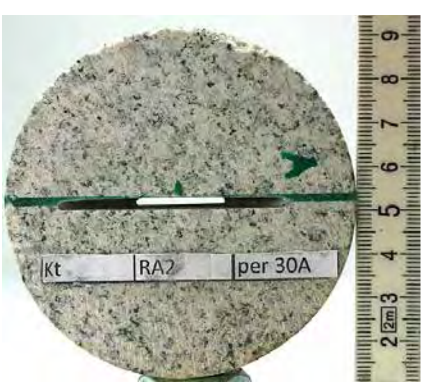
Sample R0839-Kt-RA1-Perpendicular_A notch



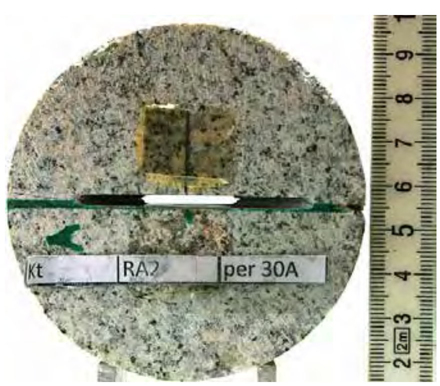
Sample R0839-Kt-RA2-Parallel_A before

Sample R0839-Kt-RA2-Parallel_A after

Sample R0839-Kt-RA2-Parallel_A notch

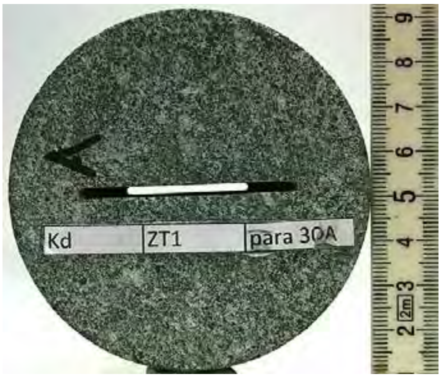


Sample R0839-Kt-RA2-Perpendicular_A before

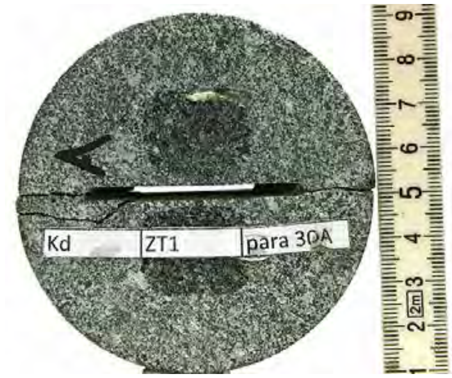


Sample R0839-Kt-RA2-Perpendicular_A after

Sample R0839-Kt-RA2-Perpendicular_A notch

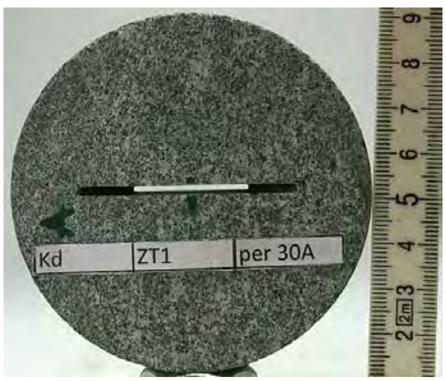


Sample R0839-Kd-ZT1-Parallel_A before

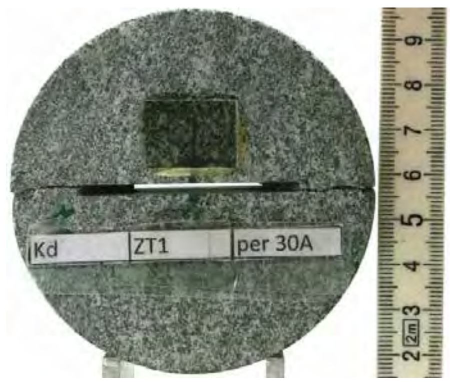


Sample R0839-Kd-ZT1-Parallel_A after

Sample R0839-Kd-ZT1-Parallel_A notch

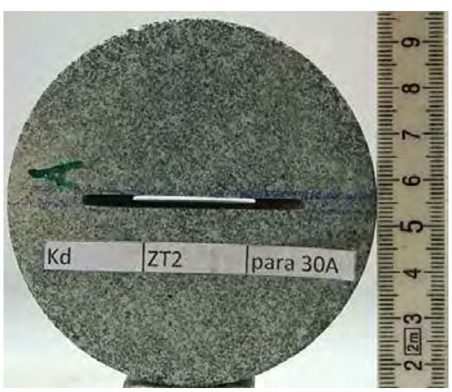


Sample R0839-Kd-ZT1-Perpendicular_A before

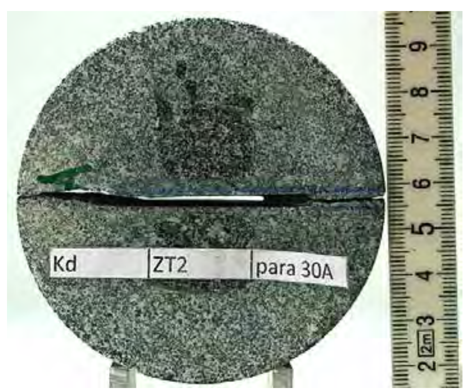


Sample R0839-Kd-ZT1-Perpendicular_A after

Sample R0839-Kd-ZT1-Perpendicular_A notch



Sample R0839-Kd-ZT2-Parallel_A before

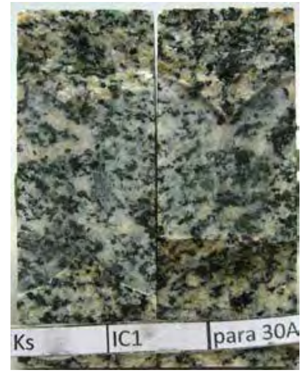


Sample R0839-Kd-ZT2-Parallel_A after

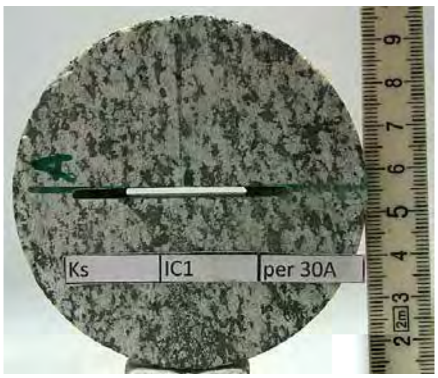
Sample R0839-Kd-ZT2-Parallel_A notch

Sample R0839-Ks-IC1-Parallel_A before

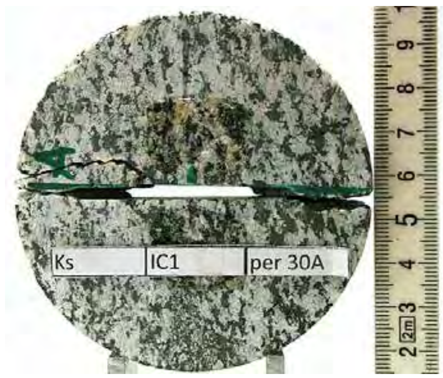
Sample R0839-Ks-IC1-Parallel_A after



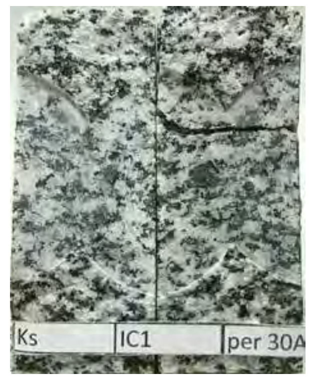
Sample R0839-Ks-IC1-Parallel_A notch



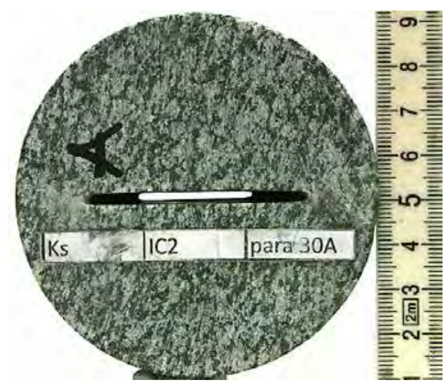
Sample R0839-Ks-IC1-Perpendicular_A before



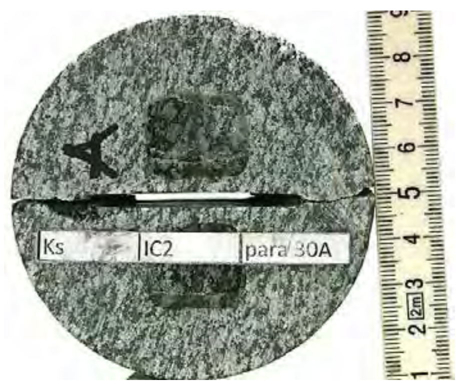
Sample R0839-Ks-IC1-Perpendicular_A after



Sample R0839-Ks-IC1-Perpendicular_A notch

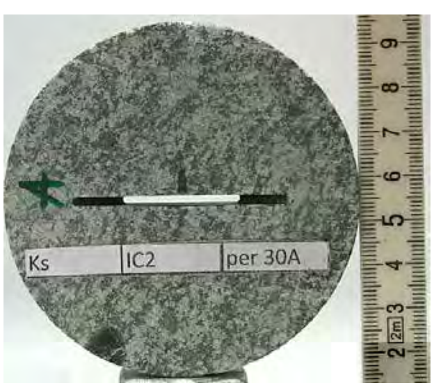


Sample R0839-Ks-IC2-Parallel_A before

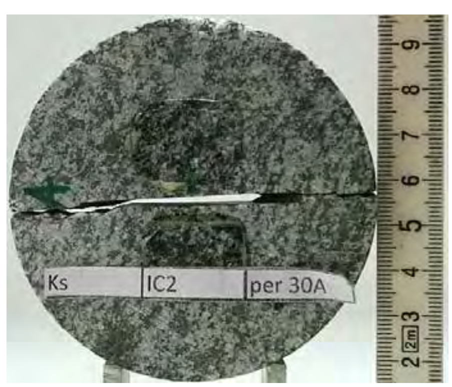


Sample R0839-Ks-IC2-Parallel_A after

Sample R0839-Ks-IC2-Parallel_A notch

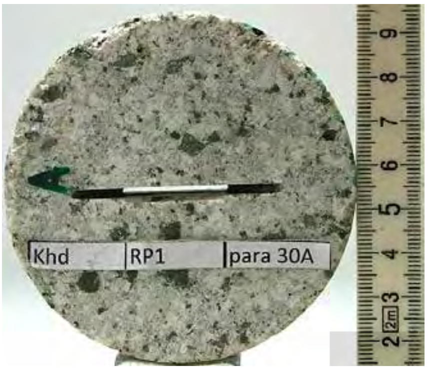


Sample R0839-Ks-IC2-Perpendicular_A before

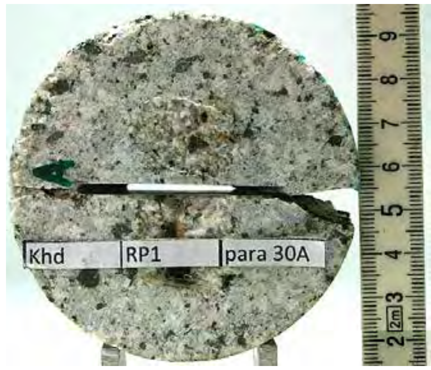


Sample R0839-Ks-IC2-Perpendicular_A after

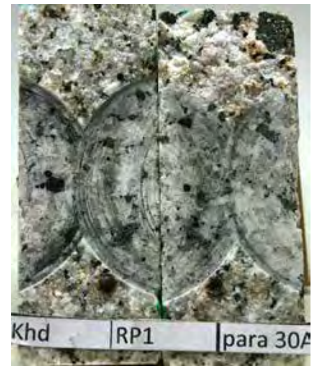
Sample R0839-Ks-IC2-Perpendicular_A notch



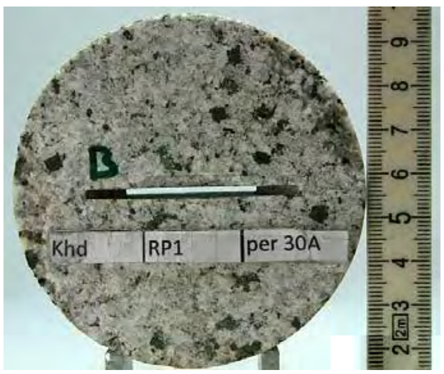
Sample R0839-Khd-RP1-Parallel_A before



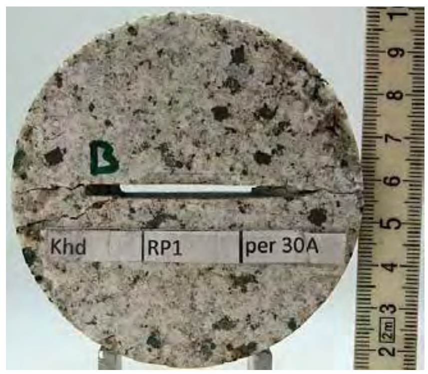
Sample R0839-Khd-RP1-Parallel_A after



Sample R0839-Khd-RP1-Parallel_A notch

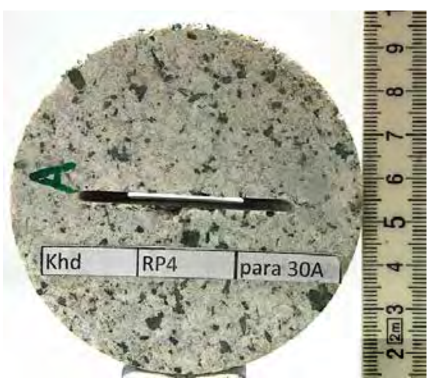


Sample R0839-Khd-RP1-Perpendicular_A before

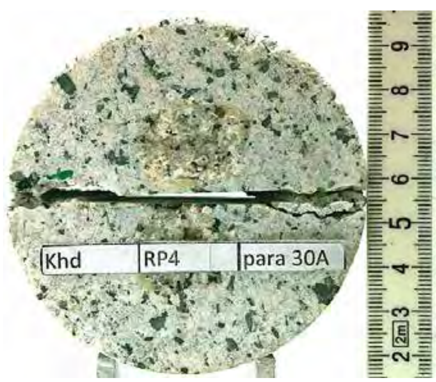


Sample R0839-Khd-RP1-Perpendicular_A after

Sample R0839-Khd-RP1-Perpendicular_A notch

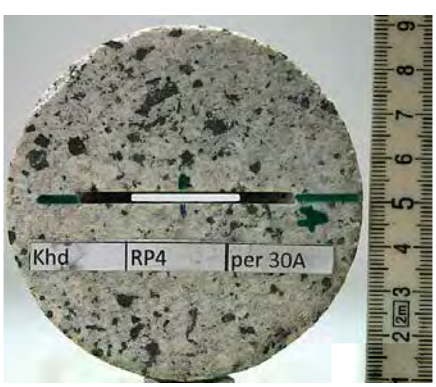


Sample R0839-Khd-RP4-Parallel_A before

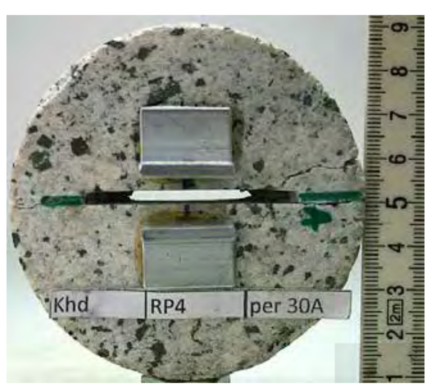


Sample R0839-Khd-RP4-Parallel_A after

Sample R0839-Khd-RP4-Parallel_A notch

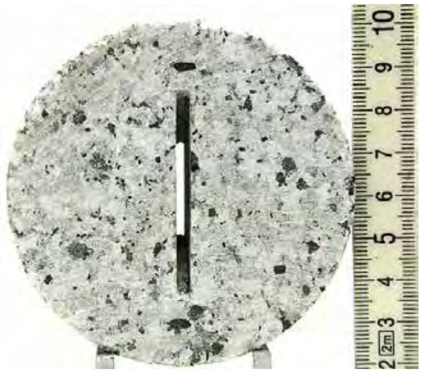


Sample R0839-Khd-RP4-Perpendicular_A before



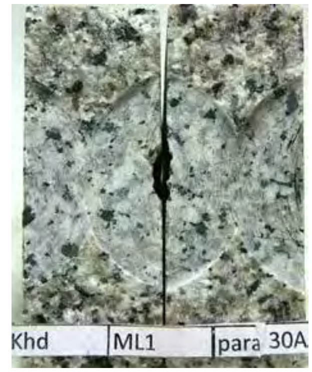
Sample R0839-Khd-RP4-Perpendicular_A after

Sample R0839-Khd-RP4-Perpendicular_A notch

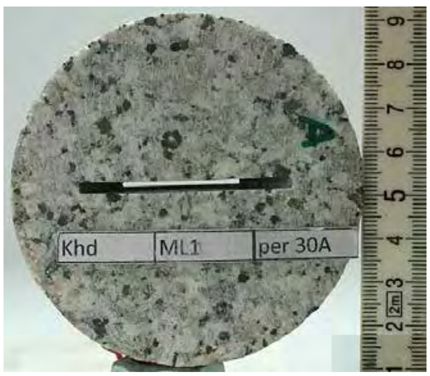


Sample R0839-Khd-ML1-Parallel_A before

Sample R0839-Khd-ML1-Parallel_A after

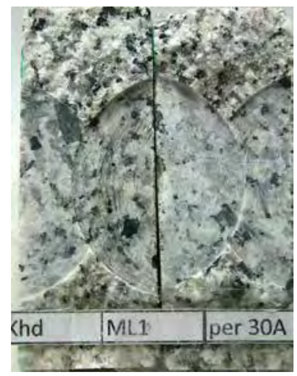


Sample R0839-Khd-ML1-Parallel_A notch



Sample R0839-Khd-ML1-Perpendicular_A before

Sample R0839-Khd-ML1-Perpendicular_A after



Sample R0839-Khd-ML1-Perpendicular_A notch

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