L A B O R A T O R Y   R E P O R T

Rock Mechanical Investigations of the Salt Formation and the Overburden of the Braskem Cavern Field Maceió

– Test Results and Parameter Evaluation –

INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

Rock Mechanical Investigations of the Salt Formation and the Overburden of the Braskem Cavern Field Maceió

– Test Results and Parameter Evaluation –

Customer:	Braskem S.A. Rua Eteno, 1561 Complexo Petroquimico de Camaçari City of Camaçari, State of Bahia Brazil
Consultant:	Institut für Gebirgsmechanik GmbH Friederikenstraße 60 04279 Leipzig GERMANY
Customer's Reference No.:	4600020847/2019
Our Reference No.:	B IfG 22/2021
Processed by:	Dipl.-Geol. Dirk Naumann Dr. Christoph Lüdeling Dr. Ali Taghichian
Place and Date:	Leipzig, 25 March 2022

Dr Christoph Lüdeling
Assistant Director

Dipl.-Geol. Dirk Naumann
Head of Geomechanical Laboratory

1 INDUCEMENT AND OBJECTIVES 4

1.1 EVOLUTION OF THE TEST PROGRAMME 4

2 CORE MATERIAL – AVAILABILITY AND CONDITIONS 7

3 THE IFG ROCK MECHANICAL LABORATORY 10

3.1 GENERAL SAMPLE CHARACTERIZATION 11
3.2 TRIAXIAL COMPRESSION TESTS (TC) – METHODOLOGY AND EQUIPMENT 12
3.3 DIRECT SHEAR TESTS (SV) – EQUIPMENT AND METHODOLOGY 17
3.4 DIRECT TENSION TESTS (DTT / HZV) – EQUIPMENT AND METHODOLOGY 20
3.5 SPLITTING TENSION ("BRAZILIAN") TESTS (STT) – EQUIPMENT AND METHODOLOGY 21
3.6 TRIAXIAL COMPRESSION CREEP TESTS (TCC) – EQUIPMENT AND METHODOLOGY 22

4 EXPERIMENTAL INVESTIGATIONS – SORTED BY LITHOLOGICAL UNITS 25

4.1 MAR – MARITUBA ARENITO 25
4.2 MAG – MARITUBA ARGELITO 27
4.3 MOS – MOSQUEIRO FORMATION 29
4.4 MRT – MARITUBA II 32
4.5 IBU – IBURA FORMATION 34
4.6 POÇÃO FORMATION 36
4.7 PAR – POÇÃO ARENITO 36
4.8 PCGL – POÇÃO CONGLOMERADO 38
4.9 PI – POÇÃO INTERCALADO 42
4.10 PF – POÇÃO FOLHELHO 43
4.11 TMS – TABULEIRO 46
4.12 PRP – PURE ROCK SALT 56
4.13 PRP – IMPURE ROCK SALT 62
4.14 SHL – SHALE FROM PARIPUERA FORMATION 62

5 SUMMARY 67

1 INDUCEMENT AND OBJECTIVES

Braskem is currently pursuing an extensive programme of field investigations and complex 3D modelling regarding the cavity field in the City of Maceió.

As inputs, the numerical simulations require geomechanical characteristics and parameters of all occurring rock formations, from the leaching horizon to the surface. Therefore, the Institut für Gebirgsmechanik GmbH (IfG Leipzig) was commissioned by Braskem with rock mechanical investigations of several geological units which occur in the region of the Maceio cavern field. The primary aim is to investigate the core material regarding its strength and deformation behaviour.

1.1 Evolution of the Test Programme

The IfG has analysed the Maceió cavern field since 2019. At the time, the local geology and the rock engineering and geomechanical properties of the salt deposit and overburden were not very well known, so the models and assessments necessarily included a number of estimates and uncertainties.

To improve the knowledge of the local situation, Braskem drilled a new well (the stratigraphic well PE04) in 2020 to obtain a drill core from the surface down to the cavern depth (well depth was approximately 1200 m). Via drill logs and on-site geological analysis, the stratigraphical, lithological and engineering geological assessment of the overburden was refined considerably; parts of the core material were sent to be tested in the rock-mechanical laboratory of the IfG and in other labs.

Braskem and IfG developed a test programme based on the requirements for the geomechanical modelling and assessment of the Maceió field.

For a reliable geomechanical model, the hydromechanical properties of the salt and overburden strata are required. Specifically, this includes

- the shear strength (peak and residual) of the rock as function of the confining stress,
- the tensile strength (preferably both horizontal and vertical for laminated rocks),
- the shear properties (peak and residual strength) of joints and weakness planes (if present) in the rock mass as a function of normal stress,
- the influence of pore pressure on the strength,
- and the creep behaviour of the salt.

The test program originally proposed consisted of triaxial compression tests with and without the application of pore pressure, shear tests on interfaces and Brazilian (splitting tensile) tests to determine the tensile strength. Based on the available data before the geological investigations, the overburden structure was classified on a simplified lithological basis (Source: Braskem), see Table 1.1:

Tab. 1-1: *Originally planned test matrix (with amount and type of tests per lithological unit).*

Lithology	TC nat	TC wet	STT (Brazil)	Permeation	Shear	Creep
Sandstone	9	9	6			
Limestone	9	9	6			
Shale	9	9	6		6	
Conglomerate	9	9	6		6	
Halite	8	8		6	6	6

Based on the geological analysis of PE04, as well as seismic studies and the investigation of other borehole data, the stratigraphy has been revised (see Figure 1-1). The overburden rocks comprise sandstones, limestones, shales and conglomerates from the Barreiras, Marituba, Mosqueiro, Muribeca, Poção and Maceió formations (in the following, the rocks from the Muribeca and Maceió formations are denoted by the names of the Ibura and Tabuleiro dos Martins members, respectively). The leaching horizon (the Paripuera formation) consists of rock salt with interbedded shale. For the heterogeneous conglomerate, both block and matrix properties influence the rock mass behaviour, as well as the interfaces.

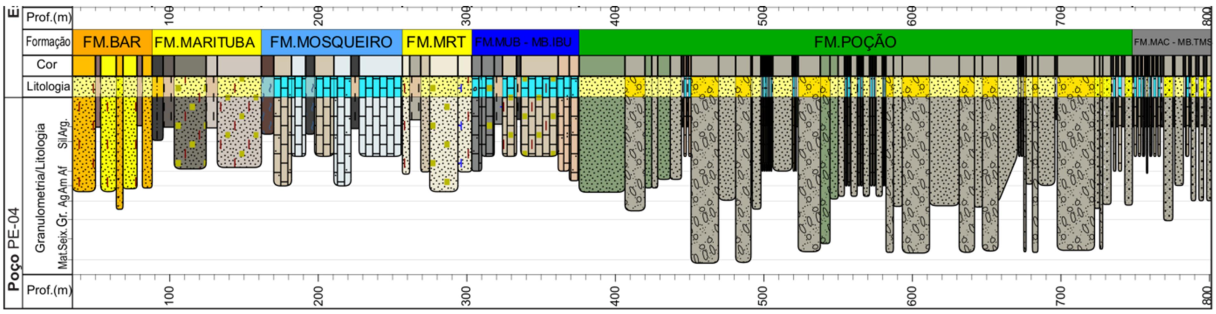


Fig. 1-1: *Lithostratigraphic column of the Maceió overburden in PE04 well (Source: Braskem)*

Braskem's team of geological experts has defined 13 rock classes (called lithological units in the following) based on the stratigraphy and lithological composition within the strata. Accordingly, IfG and Braskem adapted the laboratory programme (also accounting for sample availability). The Barreiras formation, which ranges from the surface to a depth of approximately 100 m, consists chiefly of overconsolidated sands and clays, which are prone to damage from vibrations and drying. Samples from the Barreiras formation could not be recovered; the IfG performed test on the other formations.

The refined test programme is shown in Appendix 5. It comprises:

- Triaxial strength tests at natural water content ("TC_nat";) for all lithological units

- Triaxial strength tests under the influence of fluids (“TC_wet”; tests were performed either under the influence of pore pressure or with samples that had been immersed in brine for several days) for the TMS unit which directly overlays the leaching horizon
- Direct tensile tests (“DTT”) for laminated shales
- Splitting tensile tests (“Brazilian”, STT) for the TMS unit
- Direct shear (“DST”) tests for suitable units. (These tests are most suitable for potential weakness planes such as laminations, lithological interfaced, clay layers, etc. The precise number of shear test for each unit was fixed based on the presence of such features.)
- Triaxial long-term creep tests (“TCC”) for the salt units

In addition, each sample is characterised petrographically.
Note that the Marituba II formation is quite thin, and the programme was reduced due to lack of samples.
Note further that the core material is stored in wrapped condition in boxes (see next section) to avoid drying or mechanical damage; samples are prepared shortly (at most a few days) before testing. Hence, the test programme is subject to changes if the envisaged specimen turns out to be not suitable.
The programme is rather extensive. To be able derive rock-mechanical parameters in time for the next numerical model, IfG and Braskem decided to perform four or five triaxial strength tests for each unit, as well as some tensile and shear tests, and the creep tests on the salt.
Altogether, a sufficient number of tests could be performed for all lithological units to derive input data for the numerical modelling.

2 CORE MATERIAL – AVAILABILITY AND CONDITIONS

In 2021 a huge amount of drill core material in ca. 250 boxes were sent to the rock mechanical laboratory of the IfG in Leipzig lab (see Figure 2-1):

Fig. 2-1: *Some of the delivered core boxes with core segments of various stratigraphical units.*

Each core box was clearly labelled with information like borehole number, core box number, depth range of extraction, core segment ID (see Figure 2-2):

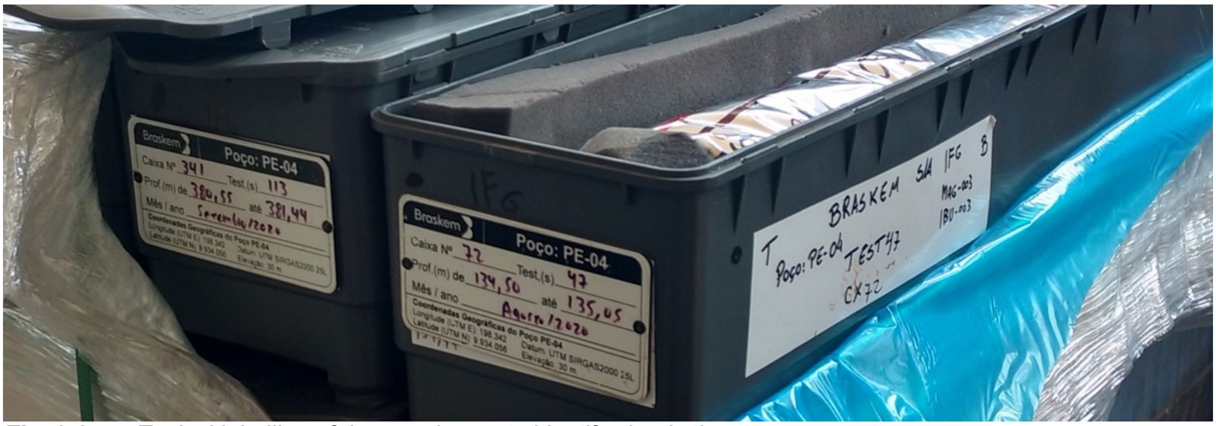


Fig. 2-2: *Typical labelling of the core boxes to identify clearly the core segments.*

In each core box, one or more core segments which were separately packed in aluminium foil (against humidity) and in aluminium half-shells and plastic end-pieces. Within these stable coating, the segments were stored (incl. another plastic foil covering to prevent humidity effects). An example is given in Figure 2-3:

Fig. 2-3: *Example of the transport and storage conditions. Top: Core segment covered in aluminium foil; Centre: stable aluminium half-shell container, Bottom: finally, the core segment covered with plastic foil.*

The delivered available core material comprised several formations with a whole suite of rock types, ranging from argillites, sandstones and limestones to conglomerates (with large pebbles/clasts in a sandstone matrix), shales and rock salt of varying purity (see Table 2-1).
We should note that the material was well packed and shipped in appropriate containers. Nevertheless, a certain amount of damage is unavoidable in transport, in particular for brittle laminated rocks or claystones that are susceptible to swelling or shrinking with humidity changes. Thus, some core segments were broken into smaller pieces that were not suitable for some test types, and in several cases the samples broke during preparation or characterisation and new specimens had to be prepared.

To a certain extent, sample selection and test schedule were thus influenced by the availability of test specimens. However, IfG has received a sufficient amount of drill core, and a test programme could be realised that allows to derive the required geomechanical parameters for the numerical simulations.

Tab. 2-1: *Overview of the rock types representing the various formations:*

Formation/Lithological unit	Rock type
MAR (Marituba Arenito)	Sandstone
MAG (Marituba Argelito)	Argillite
MOS (Mosqueiro)	Limestone
MRT (Marituba II)	Sandstone
IBU (Ibura)	Limestone
PAR (Poção Arenito)	Sandstone
PCGL (Poção Conglomerado)	Conglomerate (w. sandstone matrix)
PI (Poção Intercalado)	Sandstones, shaly and calcarenitic intercalations
PF (Poção Folhelho)	Shales with intercalations
TMS (Tabuleiro)	Shale
PRP Pure Halite	Pure rock salt
PRP Intercalated Halite	Rock salt with impurities
PRP Shale from Halite	Shale

3 THE IFG ROCK MECHANICAL LABORATORY

The following conditions and equipment are available in the IfG labs for rock mechanical laboratory investigations:

- Climate-controlled rooms for storage of specimens at conditions which correspond to those present in situ
- Laboratory for mineral-petrographic examinations, density and moisture determination, ultra-sound measurements and photographic documentation
- Workshop for the preparation of specimens in high precision according to testing requirements
- Test laboratory containing various servo-controlled hydraulic testing machines for conducting investigations on rock mechanics in accordance with the up-to-date state of science and technology (see Figure 3-1).

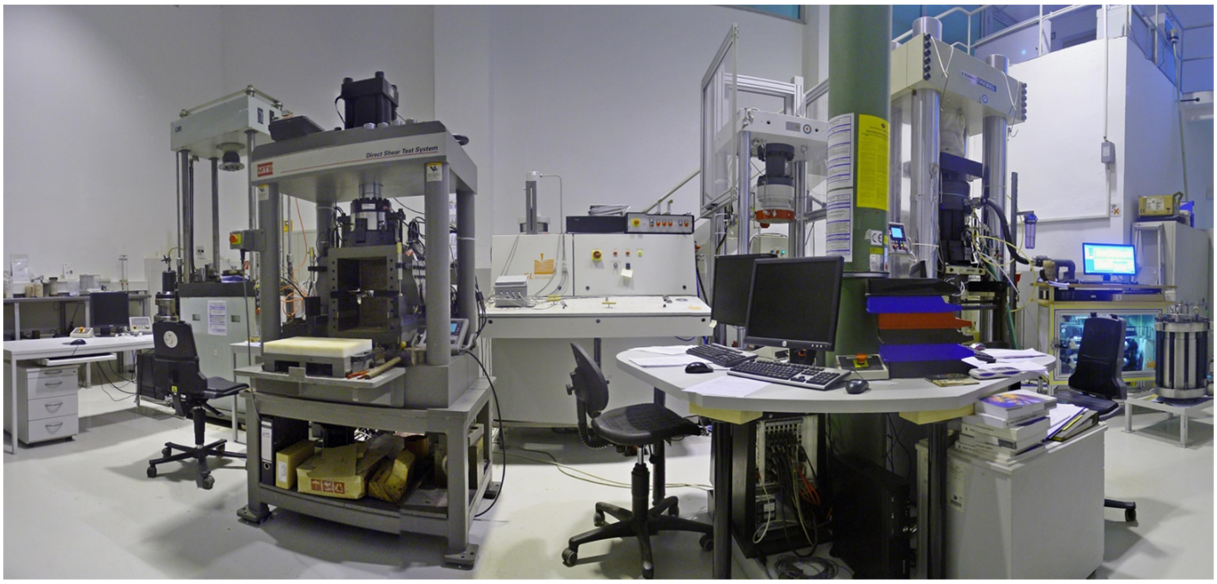


Fig. 3-1: *View inside the rock mechanical lab with various servo-controlled hydraulic testing machines.*

It has to be mentioned that some of the applied IfG[2] test procedures have been developed for the requirements of the IfG material laws. But generally they are in accordance to ASTM standards resp. equivalent descriptions, e.g.:

- ASTM D 4543-85 Standard Practice for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances
- ASTM D 2845-05 Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock
- ASTM D 2664-86 Standard Test for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements

[2] IfG Leipzig is certified pursuant to ISO 9001:2015.

- DGGT (1979): Empfehlung Nr. 2 des AK 19 der DGEG (Dreiaxiale Druckversuche).
- ASTM D4406-04 Standard Test Method for Creep of Cylindrical Rock Core Specimens in Triaxial Compression
- ASTM D7070-04 Standard Test Method for Creep of Rock Core Under Constant Stress and Temperature
- ASTM D3967-16/ Splitting Tensile Strength of Intact Rock Core Specimens

3.1 General Sample Characterization

The machining of the core segments was done with a rock cutting saw and a lathe. It is of urgent need to perform these works very precise and under consideration of a care handling (to prevent external influences). After preparing the cylindrical shaped samples in the IfG labs, their density was determined by measuring the geometrical dimensions and the mass. Concerning the quality of these parameters it has to be noted that the accuracy in length determination is < 0.02 mm, the one in mass determination is ≤ 0.02g (for samples with m ≤ 200 g) and ≤ 0.1 g (for samples with m > 200 g).

Additionally, ultrasonic investigations were carried out to check integrity, homogeneity and isotropy of the samples. The ultrasonic pulse measurement system used for transmission of the rock specimens consists of two transducer sets for P-waves, respectively S-waves and a receiver system for generating and evaluating the ultrasonic signals. The specimen is placed in physical contact between two piezoelectric transducers, one acts as a driver and the other one acts as a receiver. The transit time of the mechanical pulse to pass through the specimen is used to determine elastic wave velocity. For samples where both P- and S-waves were measured in axial sample direction the elastic constants are obtained from density (ρ) and the ultrasonic velocities (v_p, v_s). Dynamic elastic parameters of the various rock portions determined on the base of sonic wave velocity at room temperature are in a wide range representing typical values for the various materials as known from other locations. In some cases no p- or s-wave velocity could be measured and there, no data of elastic constants (E, K, G and ν) are available.

The results of the sample characterization are given in the tables in the Appendix of this lab report.

3.2 Triaxial Compression Tests (TC) – Methodology and Equipment

Triaxial compression tests (TC) are executed on cylindrical core samples with dimensions of e.g. 200*100 mm (generally a 2:1 ratio of height to diameter) in one of two available servo-hydraulic testing machines of the IfG lab (RBA 2500, Schenk/Trebel, Germany and D2000 GGL Testsystems – using the MTS-TestStar software; see Figure 3-1) generating the necessary stress σ_1 in axial direction and σ_3 in lateral direction. In these servo-hydraulic machines complex test procedures can be realised (e.g. simple single-stage uniaxial and triaxial tests, tests with acting fluid pressure, tests with permeation of gases or fluids, relaxation tests etc.). Very high confining pressure conditions (up to 1000 bar) can be applied to the samples (even with raised temperatures of up to 180°C). The maximum axial force is 2500 kN.

The cylindrical samples are sealed with rubber tubes and oil is used as confining medium. Outside the vessel three LVDT transducers are mounted between the piston and the load frame near the sample for the measurement of the axial strain. The sensors for force, pressure and displacement were calibrated by MTS Germany in 02/2020. The axial load is determined from an external load cell. In this project, most tests have been carried out at room temperature (ca. 24°C; except the salt rocks, where the influence of temperature has an obvious effect to the strength and deformation behaviour and properties). During all tests the following parameters are measured automatically: the axial deformation Δh, axial load F and the confining pressure p = σ_3. The conversion of the measured values to effective stress and strain is given as:

$$\sigma_{eff} = \left(\frac{F}{A_0} - \sigma_3\right)(1 - \varepsilon_1)$$

$$\varepsilon_1 = \frac{h_0 - h}{h_0}$$

with:

h_0 , h	length of the sample before and during the deformation
A_0	cross sectional area of the undeformed sample
F	axial load
σ_3	confining pressure

The term (1-ε_1) in results from the consideration of the sample bulge during the deformation, e.g. the changes of the (average) cross sectional area in compression as well as in extension were regarded.

In addition, as a standard technique of IfG during the triaxial strength experiments the sample volume changes ΔV are determined by a volume balance of the mantle oil volume changes as measured via the pressure intensifier and the axial piston displacement in the cell:

$$\Delta V = \Delta h \cdot A_{PP} - \Delta S_{PI} \cdot A_{PI}$$

with ΔS_{PI} = displacement of the cylinder within the pressure intensifier

A_{PI} = cross section of the piston within the pressure intensifier

Δh = displacement of the piston of the triaxial cell

A_{PP} = cross section of the piston of the triaxial cell.

$$\varepsilon_V = \frac{\Delta V}{V_0}$$

The volume change of the sample corresponds to the parameter dilatancy. To ensure volume constancy in the load system after each pressure change waiting period of at least 1 hour has been applied for stable conditions.

The conventional triaxial test procedure is as follows: at constant confining pressure the sample is axially loaded using a constant deformation rate ($2.5*10^{-5}$ s^{-1} for the salt rocks and $1.0*10^{-5}$ s^{-1} for the more brittle overburden rocks), until the sample fails and reaching the post failure state. Here, triaxial compression tests (TC) with constant confining pressures between 1 – 16 MPa were realised to investigate the deformation-dependent strength and dilatancy behaviour. After the failure occurs the axial load decreases with further deformation due to the decrease of the load-bearing capacity becoming nearly constant if the post-failure stage is reached. For the salt rock investigations and the so-called “TC_nat”-tests of the overburden rocks the test would be finished here and the sample is unloaded. A typical stress-strain diagram of a single-stage triaxial compression test is show in Figure 3-2.

From the TC tests, we derive the elastic parameters by considering stresses and strains at 50% of the peak stress. To distinguish these values from the dynamic elastic constants derived from the ultrasonic wave velocities, we denote them by a subscript “50”, e.g. E_{50}. Note that for samples that do not behave purely elastic in the pre-failure regime, this approach provides one possible estimate of the elastic moduli.

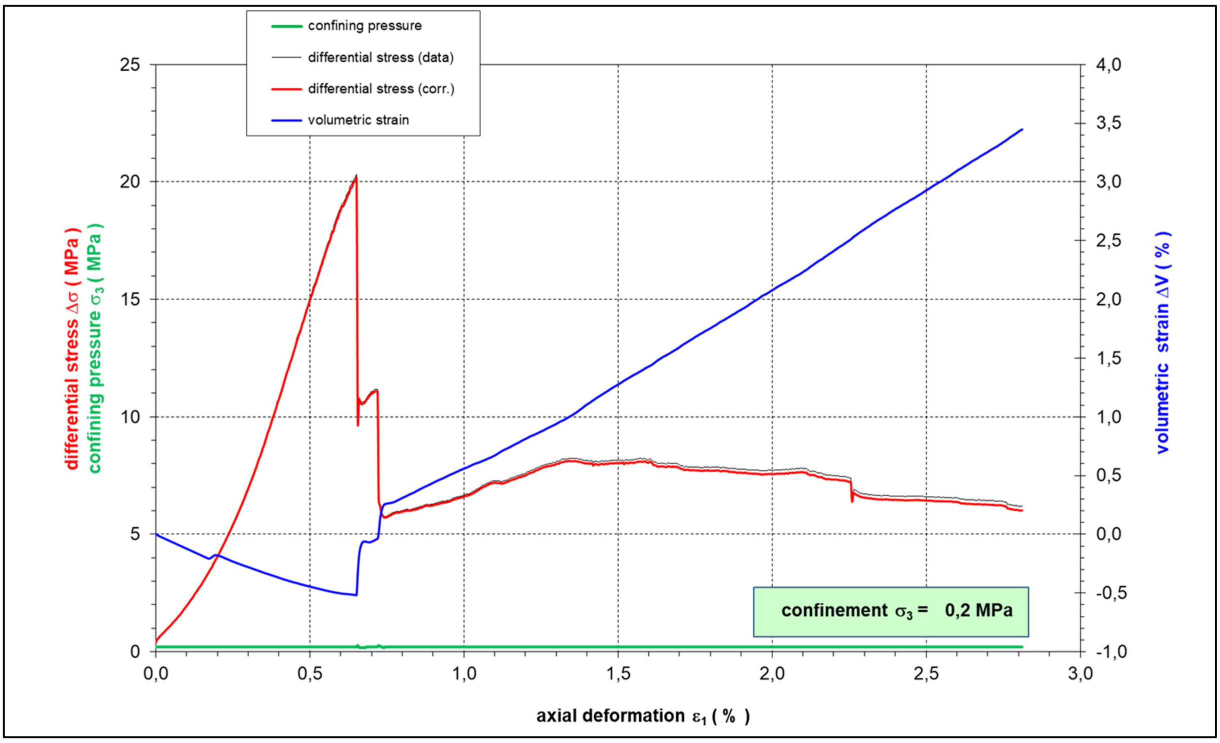


Fig. 3-2: *Typical course of a single-stage triaxial strength test at constant confining pressure conditions (0.2 MPa). Here, the stress-strain-progress of a brittle behaving overburden rock sample is shown (including the obvious drop of the differential stress after reaching the peak strength at ca. 20 MPa).*

For the overburden rocks, it was additionally of interest to investigate the influence of an acting pore pressure. Therefore, the sample (without any acting pore pressure) was axially unloaded. Then, a pressure in the range of half of the confining pressure (which was held constant) was applied (using a pump and oil as the pore pressure medium). Thus, the influence of the applied pore pressure to the residual strength could be analysed (see stress level at points (2) and (3) in Figure 3-3). Finally the pore pressure was removed completely. The procedure is also described in Figure 3-4).

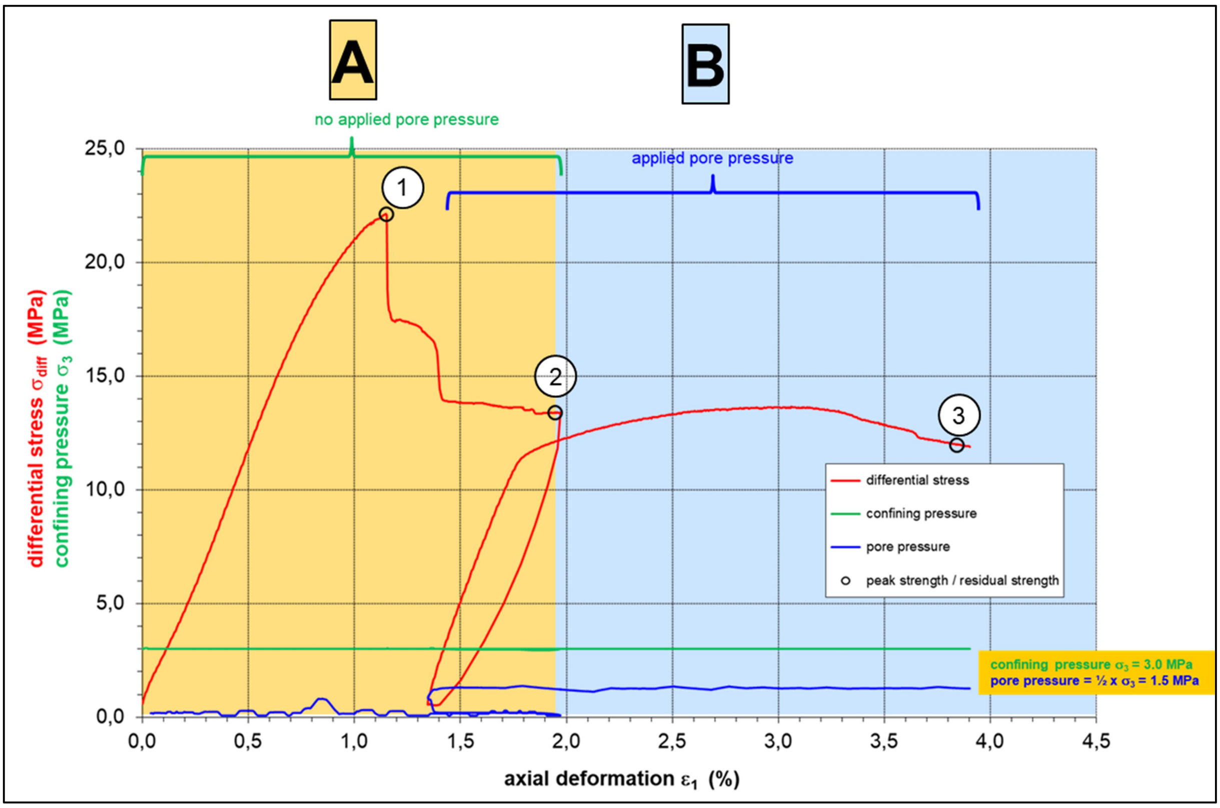


Fig. 3-3: *Typical course of a two-stage triaxial strength test including a stage of applied pore pressure (B). In both stages A and B the confining pressure was held constant (3 MPa). In A there was no acting pore pressure but in B the pore pressure was p=0.5*σ_3 (= 1.5 MPa).*

procedures of the pore pressure test:	result:	
→ conventional deviatoric triaxial strength test with applied confining pressure of (σ_3 = n MPa) without any pore pressure (p_{fl} = 0 MPa); reaching peak strength	→ maximum / peak strength value (phase 1)	A
→ continuation until residual strength niveau		
→ unloading-reloading cycle	→ residual strength value (phase 2)	
→ reloading cycle and applying pore pressure (σ_3 = n MPa, p_{fl} = 0.5*n MPa)	→ residual strength value (phase 3)	B

Fig. 3-4: *Procedures of the pore-pressure TC test and the derived results from each variation.*

Another option for the realization of triaxial compression strength tests is the TC test with saturated samples. Here, the prepared samples were stored in a cylinder and totally covered with brine. Such type of tests allows to analyse the influence of fluids (like brine) on the stress-strain behaviour. It has to be noted that it was not the aim to realise a complete saturation of the sample (which would take much longer times or the usage of a vacuum). Here, the focus was on the possible impact of the fluid which may penetrate along micro-cracks into the sample (which was at natural humidity) and affect the stress-strain properties of partly saturated portions (see Figure 3-5).

Fig. 3-5: *Left: prepared sample under "natural humidity" conditions; Centre: Cylinder in which the samples were totally covered with brine (for 24 h); Right: wet sample after saturation process.*

The test results will be presented in Section 4. The dominant fracture pattern for each sample will be classified according to the following table:

Tab. 3-1: *Fracture types for TC samples*

Type	Description	Examples
A	Axial splitting: Predominantly vertical cracks	
B	Shear failure: Single or double diagonal cracks	 
B*	Like type B, but failure on lamination/bedding plane	

C	Horizontal cracks	
C*	Like type C, but failure on lamination/bedding plane	
D	Plastic deformation without visible cracks	
E	Irregular cracks or disintegration into many pieces	

We should note that this classification is a qualitative description; specific samples may fail in a way that combines elements of several fracture types.

3.3 Direct Shear Tests (SV) – Equipment and Methodology

Bedding planes in foliated rocks, in addition to rock joints and other geomechanical discontinuities, are probably the clearest example of existing interfaces (e.g. Minkley & Mühlbauer[3]). For the mechanical behaviour of interfaces the relevant variables are stress traction vector with one normal component and one tangential in a simple two-dimensional stress field (or two tangential stresses in 3D), and the conjugate "strain" variables are the corresponding relative displacements. However, such stress conditions can be only realised in direct shear tests, which are indispensable to reproduce slip between various materials or even within (mono-) materials with bedding planes resulting from sedimentation and geological processes.

[3] Minkley W. & Mühlbauer J.: “Constitutive models to describe the mechanical behaviour of salt rocks and the imbedded weakness planes”; Proc. 6th Conference on the Mechanical Behaviour of Salt, Hannover, 22-25 May 2007

The slip criterion for a weakness plane in the stratum, e.g. bedding planes, is referred to in the literature by many different terms: shear strength, failure criterion, yield criterion, or Coulomb criterion. It is often expressed as an equation that stipulates the maximum permissible shear stress along the slip surface being analysed. The simplest formulation, the linear Mohr-Coulomb (MC) criterion, can be written as

$$\tau_{max} = c' + \sigma'_n \cdot \tan \Phi'$$

with

τ_{max} = the maximum shear stress that the plane can sustain before slip;

c' = the cohesion of the rock;

σ'_n = the normal effective stress across the slip plane; and

Φ' the internal friction angle.

The material parameters c' and ϕ' are determined empirically from testing.

In the past, several companies have developed modern testing equipment which allows new types of testing procedures to determine the mechanical parameters of joints and intact rock. High-response servo-hydraulic systems with digital control technology, strain measurement equipment mounted onto the specimen and programmable control modes, enable new types of test procedures to be performed, which are tailored to the specific problem, e.g. Bluemel (2000)[4]; Bluemel & Poetsch (2003)[5]. For realization of required shear tests a modern shear test system is available in the IfG Leipzig labs (Figure 3-6).

The loading frame consists of a two-axle experimental setup with vertical and horizontal stress initiation, a platform for shear test in a shear box, and a servo-hydraulic control unit for two channels (vertical and horizontal). Both can be managed force or displacement controlled. The frontal part is an extremely stiff four-columned test frame for fixing and vertical loading of the two-part shear box by the upper hydraulic cylinder (up to 500 kN axial load).

Horizontal motion is guided by a precision linear bearing, which is designed for low friction and a single degree of freedom (translation only). The horizontal force is generated by a laterally positioned horizontal cylinder (up to 250 kN pressure, 160 kN tension). The upper part of the shear box is fixed by a horizontal housing that enables yet a twisting of approx. 2° around the horizontal axes referring to the shear midpoint. While a vertical load acts to the whole shear box the lower box can be horizontally displaced under load.

[4] Bluemel, M., 2000. Improved procedures for laboratory rock testing. EUROCK 2000. ISRM Symposium Aachen, 573 – 578.

[5] Bluemel, M., Poetsch, M., 2003. Direct shear testing system. International Symposium on GeoTechnical Measurements and Modelling, Karlsruhe, 327 – 331.

The layout of the LVDT's (Linear Variable Differential Transformer), which are positioned at the initial specimen joint shear plane in multiple locations (4 vertical and 2 horizontal LVDT), guarantee that the dilatancy, the shear displacement and the rotations can accurately be measured.

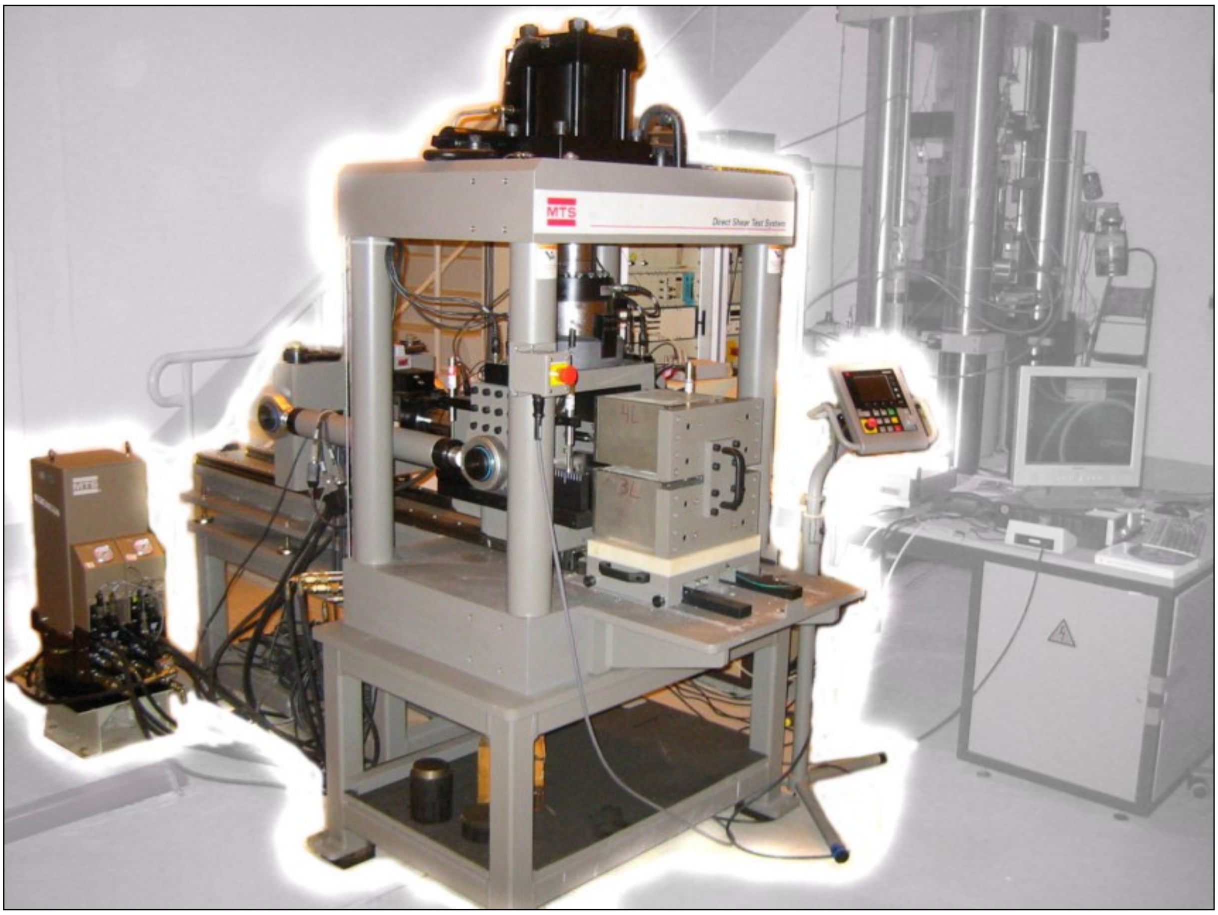


Fig. 3-6: *The MTS – shear test system (model 816) for direct shear tests.*

Generally, intact or naturally jointed specimens up to 200 mm dimension can be tested in direct shear. A sufficiently stiff fixing of the specimens is a prerequisite for an exact determination of shear resistance. Therefore, first of all the specimen is orientated in a position where the line of action of the shear force (τ) is on the investigated interface and the line of action of the normal stress (σ_n) is perpendicularly to that plane. Consequently both shear boxes will be filled in succession with high-strength anchor cement mortar. Thus, a shear slit of about 20 mm width remains that enables the shear test of the fixed specimen.

For characterization of the bedding plane behaviour a constant normal stress is applied, and then kept constant while shear relative displacement is applied to the sample. The measured values include shear stress and normal displacement, in addition to dilatancy, e.g., compaction or up-gliding corresponding to displacement in the direction of σ_n. The test is commonly continued in two steps with increased values of normal stress focusing on the residual strength. Therefore, the shear stress increases with further shear deformation until the sample fails at the weakening plane (maximum peak value). Then, the shear strength reduces up to a plateau: the residual strength.

3.4 Direct Tension Tests (DTT / HZV) – Equipment and Methodology

Another testing method of analysing potential weakness planes is the execution of direct tension tests. The determination of the maximum tension strength was realised by using a servo-hydraulic testing system SHM250 by WPM Leipzig (see Figure 3-7). The stress is measured via a load cell at the top of the testing frame. The tension stress is applied to the sample via a bonded plate at the top (and a second one at the bottom) of the sample. The bondage of the sample to the end-plates was ensured by using a high-strength 2-component-glue (“Araldite”).

Stress, strain and testing duration is recorded while testing. The standard deformation rate is $1 \cdot 10^{-5}$ mm/s. The test will be stopped after obvious exceeding of a tension stress limit which is often characterised by an abrupt failure and decrease of the applied tension stress.

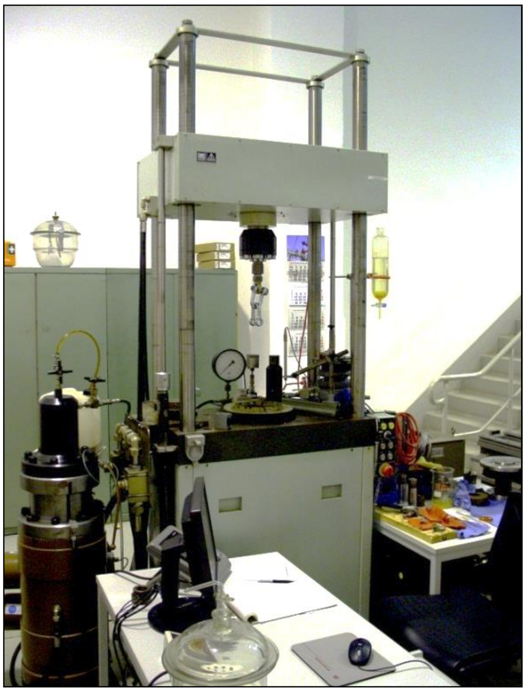


Fig. 3-7: *left: servo-hydraulic testing system SHM 250 and right: sample after a direct tension test (note the obvious bedding planes on the clear failure on such plane).*

The tension strength σ_{DTT} results from the maximum axial load $F_{\max}$ and the cross-sectional area A_0:

$$\sigma_{DTT} = \frac{F_{\max}}{A_0}.$$

3.5 Splitting Tension ("Brazilian") Tests (STT) – Equipment and Methodology

The SHM 250 servo-hydraulic testing machine (manufacturer: WPM Leipzig; see above), which can be operated in force and deformation control mode, is available, among other things, for carrying out the splitting tensile tests (Brazilian test) for indirect determination of the tensile strength σ_{STT} in accordance with DIN 18136. The force is measured by a load cell attached to the crosshead of the testing machine. For the tensile splitting tests, a test arrangement with two guided load frames is used. Here, the load is transmitted via the compression – in the form of a strip – to the horizontal disc-shaped test specimen (see Figure 3-8 left), which is clamped between two load frames that are connected to each other by guiding rods (Figure 3-8, right).

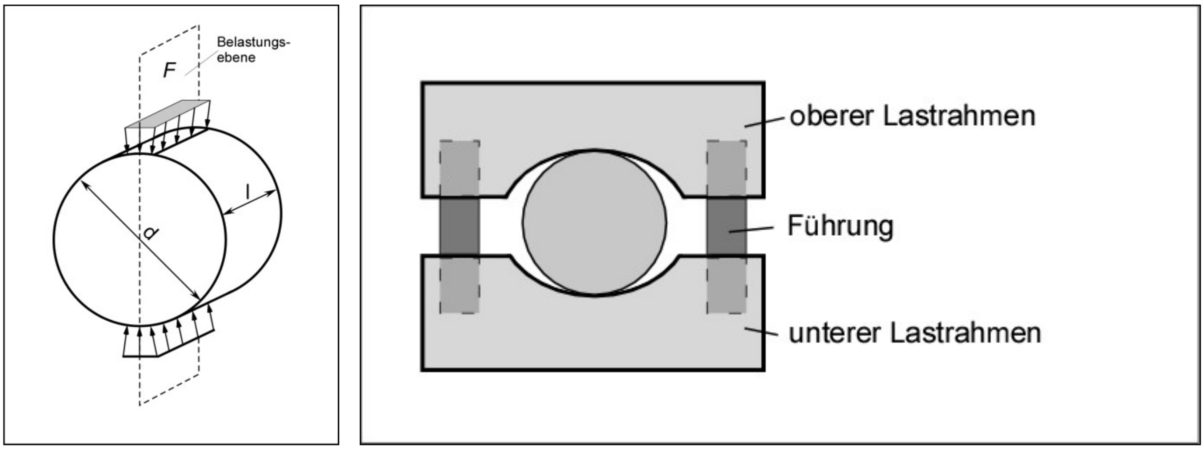


Fig. 3-8: *<u>left:</u> sketch of the load-application to the BRAZIL-test sample and <u>right:</u> sketch of the load-frame where the sample is clamped.*

When the compressive force is applied, this structure causes a wedge-shaped propagation of the pressure into the test specimen. This generates a tensile stress along the centre of the test specimen (see Figure 3-9). From the force and the test specimen geometry, the tensile strength can be calculated approximately according to the theory of elasticity:

$$\sigma_{STT} = \frac{2 \cdot F}{\pi \cdot (d \cdot l)}$$

σ_{STT} = tensile strength

F = force

d = sample diameter

l = sample length

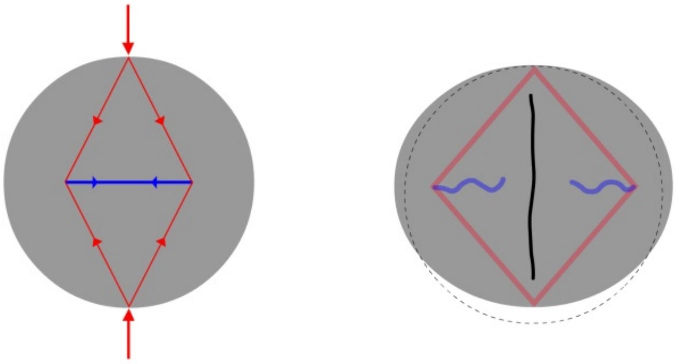


Fig. 3-9: *Principle of the BRAZIL-test.*

3.6 Triaxial Compression Creep Tests (TCC) – Equipment and Methodology

The time-dependent creep of salt rocks can be divided into three stages. The first stage, or primary creep, starts at a rapid rate and slows with time. Second stage (secondary) creep has a relatively constant rate. Third stage (tertiary) creep, possible if the stress state exceeds the dilatancy boundary, has an accelerating creep rate and terminates by failure of material due to rupture.

With respect to a prognosis of the convergence of the underground opening during and after the excavation process the long-term behaviour of salt, i.e. the secondary creep, must be known. Secondary creep is characterised by a constant strain rate generated by a constant stress (after a transient phase) with a highly non-linear stress influence on the strain rates. For its investigation creep tests are being performed.

To determine the creep properties, a cylindrical sample is subjected to prolonged compression loading at constant temperature. IfG has numerous testing rigs for long-term creep tests in climate-controlled laboratories (see Figure 3-10). The triaxial cells, used for testing at compressional and extensional stress regimes, can be heated up to 120°C. The test condition can be varied applying confining pressures up to 30 MPa, while the axial load is in a range up to 200 kN.

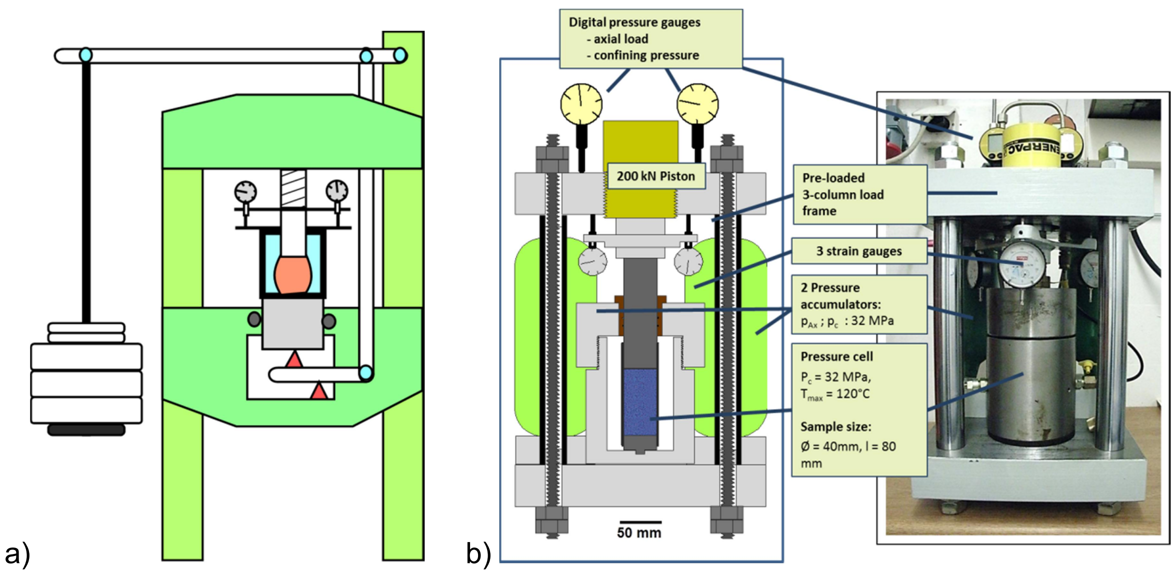


Fig. 3-10: *Creep test devices, available at IfG. a) Weight-controlled standard creep test rig (sample standard size: d = 40 mm, h = 80 mm). b) New creep test rig with hydraulic stress control with pressure accumulators (sample size: up to d = 60 mm, h = 120 mm).*

From the available salt core segments (PRP unit – pure halite and rock salt with impurities) defined cylindrical test samples were prepared in a lathe. The samples diameter (d = 40 mm) and the height (h = 80 mm) are limited from the test device. The specimens are sealed with a rubber jacket to protect them against the confining pressure medium after installation in the cell.

The cell itself is typically located in a loading frame to apply the axial forces. The axial stress and the confining pressure result from a hydraulic system kept constant by an accumulator. The axial load is determined by a calibrated load cell before each experiment. The confining pressure was checked by pressure transducers. Both parameters are kept constant with an accuracy of ± 1% during the tests. After installing the test samples in the triaxial cell, both, the axial and the radial stresses are increased simultaneously. When the preferred hydrostatic stress level is reached, both, confining pressure and axial stress are kept constant for several days to ensure temperature equilibrium. Then the samples are deviatoric loaded by increasing the axial stress.

The first deformation measurement immediately after the loading phase leads to the start values for creep deformation Δh_{cr} (0) and lifetime (t = 0). The deformation measurement are being carried out using three dial gauges fixed around the samples, each one 120° hocked. The accuracy of the measured deformations is ±0.001 mm.

To ensure constant stresses during the test the axial load was stepwise increased corresponding to the lateral strain assuming that the cross section is

$$A(\varepsilon) = \frac{A_0}{(1-\varepsilon)}$$

with $\varepsilon = \frac{\Delta h}{h_0}$

All test parameters like deformation, confining pressure and temperature were checked and recorded daily.

To represent the creep behaviour the secondary creep rates ε_{cs} are estimated from a linear fit of the quasi-linear creep phases during the measured creep. The results are presented in a double-logarithmic diagram of creep rate v differential stress.

The resulting secondary creep rate is essentially a function of the 2nd invariant of the stress deviator resulting from the differential stress[6]:

$$\sigma_{Diff} = \sqrt{\frac{1}{2} \cdot \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]}$$

[6] Note that this quantity is sometimes called „effective stress“. This should not be confused with the effective stress as difference of total stress and pore pressure.

4 EXPERIMENTAL INVESTIGATIONS – SORTED BY LITHOLOGICAL UNITS

4.1 MAR – Marituba Arenito

The cores of rocks which represent the MAR – Marituba Arenito were extracted from a depth range of 120 m to 161 m. They consist of fine sandstones (arenites) with grain sizes of < 2 mm. They were compact and very homogenous rocks without any obvious bedding, other layering or joints. Although they had no bedding or oriented components, ultrasonic measurements were not possible. Their densities were in the range of 2.16 g/cm³.

Five samples were prepared to investigate the strength and deformation behaviour of MAR specimens with triaxial compression strength tests (TC_nat). The strength tests were carried out by applying confining pressures in the range of $0.2 \leq \sigma_3 \leq 5.0$ MPa with a constant deformation rate of $\dot{\varepsilon} = 1.0 \cdot 10^{-5}\, s^{-1}$ at room temperature conditions.

The results of the individual samples are depicted in the Appendices 6–16 in the form of a summary table and plot of peak strengths, photos of the samples before and after the test and individual stress – strain diagrams (differential stress and volumetric strain v axial strain). The test conditions and key results are given in Table 4-1.

Tab. 4-1: *Strength and deformation parameters of triaxially tested Marituba Arenito (MAR) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/MAR003 /TC_d1**	**743/MAR030 /TC_d2**	**743/MAR028 /TC_d3**	**743/MAR029 /TC_d4**	**743/MAR029 /TC_d5**
Formation	**MAR**	**MAR**	**MAR**	**MAR**	**MAR**
Sample	**MAR_003**	**MAR_030**	**MAR_028**	**MAR_029**	**MAR_029**
Length l (mm)	192.608	178.480	183.718	190.180	176.373
Diameter d (mm)	97.512	97.768	96.433	98.027	98.303
Ratio l_o/d_o	1.98	1.83	1.91	1.94	1.79
Mass M (g)	2859.30	2900.1	2894.1	3109.0	2871.2
Area A (cm²)	74.680	75.073	73.037	75.471	75.897
Volume V (cm³)	1438.40	1339.90	1341.82	1435.31	1338.61
Density ρ (g/cm³)	1.988	2.164	2.157	2.166	2.145
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 (MPa)	0.2	0.5	1.0	3.0	5.0
σ_{Dil} (MPa)	2.3	2.3	3.4	7.2	10.1
ΔV_{Dil} (%)	-0.27	-0.29	-0.47	-0.74	-1.12
ε_{Dil} (%)	0.44	0.68	1.09	2.15	4.24
σ_{Fail} (MPa)	3.0	2.9	4.0	8.0	11.0

ΔV_{Fail} (%)	-0.14	0.19	-0.32	-0.50	-0.63
ε_{Fail} (%)	0.71	2.04	1.95	4.08	10.92
σ_{1Fail} (MPa)	3.18	3.39	5.04	11.04	15.99
Fracture type	B	C	C	D	D
E_{50} (GPa)	0.63	0.66	0.59	0.79	0.70
ν_{50}	0.18	0.31	0.33	0.38	0.40
K_{50} (GPa)	0.33	0.57	0.58	1.07	1.21
G_{50} (GPa)	0.27	0.25	0.22	0.29	0.25

Summarised results from the triaxial compression tests are represented in Figure 4-1 in the form of stress–strain–diagrams. The curves illustrate the dependency of the load bearing capacity and the dilatancy on the deformation at different confining pressures (σ_3). The depicted curves of the 5 samples show the expected stress-strain respectively dilatancy behaviour of fine-grained compacted sandstones. It is obvious that the samples do not show brittle behaviour but do only moderately decrease after reaching the peak strength level. This is similar to the behaviour of ductile materials (at high confinement).

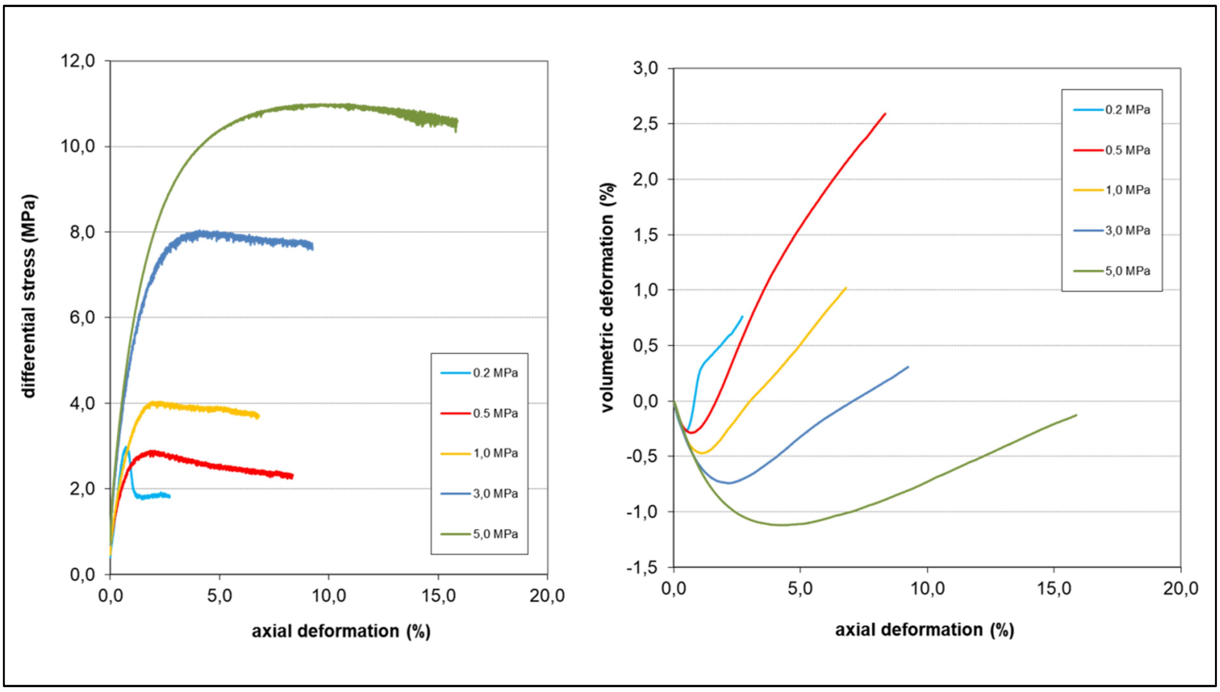


Fig. 4-1: *Left: stress-strain-diagram and Right: dilatancy-strain-diagram of the arenite samples from the MAR formation (short-term triaxial compression tests with confining pressures of σ_3 = 0.2 to 5 MPa).*

As to be seen in Appendix 9, the strength dependence on the confinement is nearly linear in the range of $\sigma_3 \leq 5$ MPa (no curved strength boundary).

In a first approach a simple Mohr-Coulomb-approach can be used, whereby based on the triaxial test results (for σ_3 = 0.2 to 5 MPa) the respective MOHR-COULOMB-parameters were determined:

ϕ – friction angle: 27.9°

c – cohesion: 0.7 MPa

Young's modulus (see Appendix 12) varies only slightly with confining stress and takes values around 0.7 GPa; Poisson's ratio is between 0.3 and 0.4 except for the smallest confining stress.

All samples and their typical failure behaviour were documented photographically (see Appendix 8).

4.2 MAG – Marituba Argelito

The next lower unit following below MAR is the MAG formation – Marituba Argelito. There the available core material is characterised by a similar habitus (compared to the MAR samples) but with more clay minerals. The cores were extracted from a depth of 129 to 156 m (followed by MAR samples, again). They were also very compact and showed no evident bedding or any layering (see photo documentation in Appendix 20).

The homogenous rock samples of MAG had a much lower bulk density (than MAR) with 1.99 g/cm³. Although they had no bedding or oriented components, ultrasonic measurements were not possible.

Up to now, four samples were prepared and tested in the IfG labs to investigate the strength and deformation behaviour by performing triaxial compression strength tests (TC_nat). The strength tests were carried out at confining pressures of $0.5 \leq \sigma_3 \leq 5.0$ MPa with a constant deformation rate of $\dot{\varepsilon} = 1.0 \cdot 10^{-5}\, s^{-1}$ at room temperature conditions.

The results of the individual samples are depicted in Appendices 25–28 in the form of a stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1) diagram. The data of the peak strengths and strains are given in the table below (Table 4-2).

Tab. 4-2: *Strength and deformation parameters of triaxially tested Marituba Argelito (MAG) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/MAG001/ TC_d1**	**743/MAG002/ TC_d2**	**743/MAG002/ TC_d3**	**743/MAG003/ TC_d4**
Formation	**MAG**	**MAG**	**MAG**	**MAG**
Sample	**MAG_001**	**MAG_002**	**MAG_002**	**MAG_003**
Length l (mm)	200.765	199.788	200.905	192.140

Diameter d (mm)	94.380	94.625	93.667	96.613
Ratio l_o/d_o	2.13	2.11	2.14	1.99
Mass M (g)	2747.80	2772.6	2826.2	2791.1
Area A (cm²)	69.960	70.324	68.907	73.310
Volume V (cm³)	1404.55	1404.98	1384.38	1408.57
Density ρ (g/cm³)	1.956	1.973	2.041	1.982
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 (MPa)	0.5	1.0	3.0	5.0
σ_{Dil} (MPa)	3.0	3.5	7.3	8.3
ΔV_{Dil} (%)	-0.19	-0.27	-0.72	-2.31
ε_{Dil} (%)	0.57	0.68	1.94	10.92
σ_{Fail} (MPa)	3.2	3.5	7.4	9.1
ΔV_{Fail} (%)	-0.16	-0.26	-0.70	-2.10
ε_{Fail} (%)	0.71	0.84	1.66	5.99
σ_{1Fail} (MPa)	3.70	4.47	10.44	14.07
Fracture type	A/E	B/E	B	B/D
E_{50} (GPa)	0.98	1.80	1.55	0.66
ν_{50}	0.37	0.40	0.39	0.40
K_{50} (GPa)	1.25	2.94	2.45	1.12
G_{50} (GPa)	0.36	0.65	0.56	0.24

Summarised results from the triaxial compression tests are represented in Figure 4-2 in the form of stress–strain–diagrams. The curves depict the dependency of the load bearing capacity and the dilatancy on the deformation at different confining pressures (σ_3). The depicted curves of the samples show stress-strain respectively dilatancy behaviour as expected. The samples do not show obvious brittle behaviour but the decrease of the differential stress after reaching the peak strength value is evident. Note that the test with 5 MPa confining stress does not show a volume increase in the post-failure region, even though the axial stress decreases and a well-defined shear plane has developed (Appendix 20).

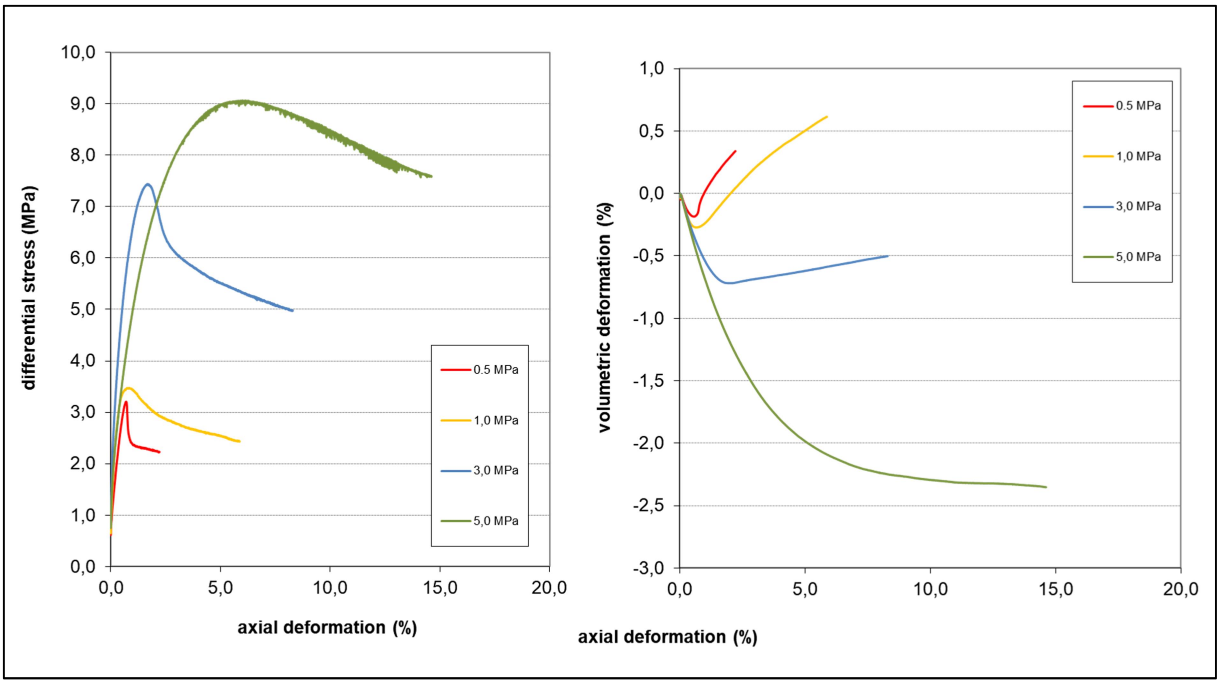


Fig. 4-2: *Left: stress-strain-diagram and Right: dilatancy-strain-diagram of the argillite samples from the MAG formation (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 5 MPa).*

As to be seen in Appendix 21, the strength depend on the confinement is nearly linear in the range of $\sigma_3 \leq 5$ MPa (no curved strength boundary).

In a first approach a simple Mohr-Coulomb-approach can be used, whereby based on the triaxial test results (for σ_3 = 0.2 to 5 MPa) the respective MOHR-COULOMB-parameters were determined:

ϕ – friction angle: 24.2°

c – cohesion: 0.8 MPa

They are comparable to those of the MAR samples.

Young's modulus (see Appendix 12) shows some scatter and takes values from 0.66 GPa to 1.8 GPa. Note that the ductile behaviour at higher confining stress underestimates the initial stiffness. Poisson's ratio is rather constant around 0.38.

4.3 MOS – Mosqueiro Formation

A number of 16 (at IfG available) core segments from the depth range between 180 and 253 m represent the MOS –Mosqueiro Formation. These are limestones of varying consolidation degree. Some look very dense and intact, others are a little bit porous. There were no bedding planes, joints or changes of material within the samples. The bulk density of tested specimens was between 2.01 and 2.40 g/cm³.

Here, 6 cylindrical specimens were prepared and tested. Again, in the sample characterisation, it was not possible to get a clear signal in the ultrasonic measurements and thus, no dynamic elastic parameters are available.

To compare the stress-strain behaviour of MOS samples with that of MAG and MAR arenites and argillites, strength tests in form of triaxial tests (at natural humidity) were performed.

The strength tests were carried out at confining pressures of $0.5 \leq \sigma_3 \leq 5.0$ MPa with a constant deformation rate of $\dot{\varepsilon} = 1.0 \cdot 10^{-5}\, s^{-1}$ at room temperature conditions. Some tests were repeated at the same confining pressure due to the variability in compactness of the samples. This led to obvious scattering in the determined strength values.

The results of the individual samples are depicted in Appendices 37–42 in the form of a stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1) . The test data and peak strength values are given in the table below (Table 4-3).

Tab. 4-3: *Strength and deformation parameters of triaxially tested limestones (MOS) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/MOS 002/ TC_d1**	**743/MOS 003/ TC_d2**	**743/MOS 005/ TC_d3**	**743/MOS 008/ TC_d4**	**743/MOS 017/ TC_d5**	**743/MOS 017/ TC_d6**
Formation	**MOS**	**MOS**	**MOS**	**MOS**	**MOS**	**MOS**
Sample	**MOS_ 002**	**MOS_ 003**	**MOS_ 005**	**MOS_ 008**	**MOS_ 017**	**MOS_ 017**
Length l (mm)	189.768	200.338	199.635	198.030	192.375	180.378
Diameter d (mm)	100.092	99.34	99.462	99.835	100.283	96.600
Ratio l_o/d_o	1.90	2.02	2.01	1.98	1.92	1.87
Mass M (g)	3589.10	3179.0	3332.4	3527.0	3049.5	2764.7
Area A (cm²)	78.684	77.507	77.697	78.281	78.985	73.290
Volume V (cm³)	1493.18	1552.75	1551.10	1550.20	1519.47	1321.99
Density ρ (g/cm³)	2.404	2.047	2.148	2.275	2.007	2.091
Temp. (°C)	**23**	**23**	**23**	**23**	**23**	**23**
σ_3 (MPa)	0.5	1.0	3.0	5.0	0.5	3.0
σ_{Dil} (MPa)	15.6	8.5	10.7	22.6	5.0	10.4
ΔV_{Dil} (%)	-0.32	-0.27	-1.17	-0.16	-0.17	-0.82
ε_{Dil} (%)	0.45	0.76	5.50	0.44	0.29	6.16
σ_{Fail} (MPa)	17.4	9.1	10.8	24.5	5.9	12.8
ΔV_{Fail} (%)	-0.30	-0.25	-1.16	-0.15	-0.16	-0.29
ε_{Fail} (%)	0.50	0.47	5.74	0.64	0.36	0.76

σ_{1Fail} (MPa)	17.88	10.10	13.80	29.48	6.40	15.75
Fracture type	A	B	B	B	B	D
E_{50} (GPa)	3.15	3.21	1.71	7.22	1.83	3.21
ν_{50}	0.11	0.20	0.35	0.37	0.23	0.39
K_{50} (GPa)	1.35	1.81	1.93	9.04	1.14	4.77
G_{50} (GPa)	1.42	1.33	0.63	2.64	0.74	1.16

Summarised results from the triaxial compression tests are represented in Figure 4-3 in the form of stress–strain–diagrams. The curves depict the dependency of the load bearing capacity and the dilatancy on the deformation at different confining pressures (σ_3). The depicted curves show an obvious scattering which results from the variations in the habitus of the limestone samples. Some show evident brittle behaviour in their failure development and test progress, others behave more moderately in its post-failure range. Both tests at 3 MPa confining stress show no post-failure dilatancy.

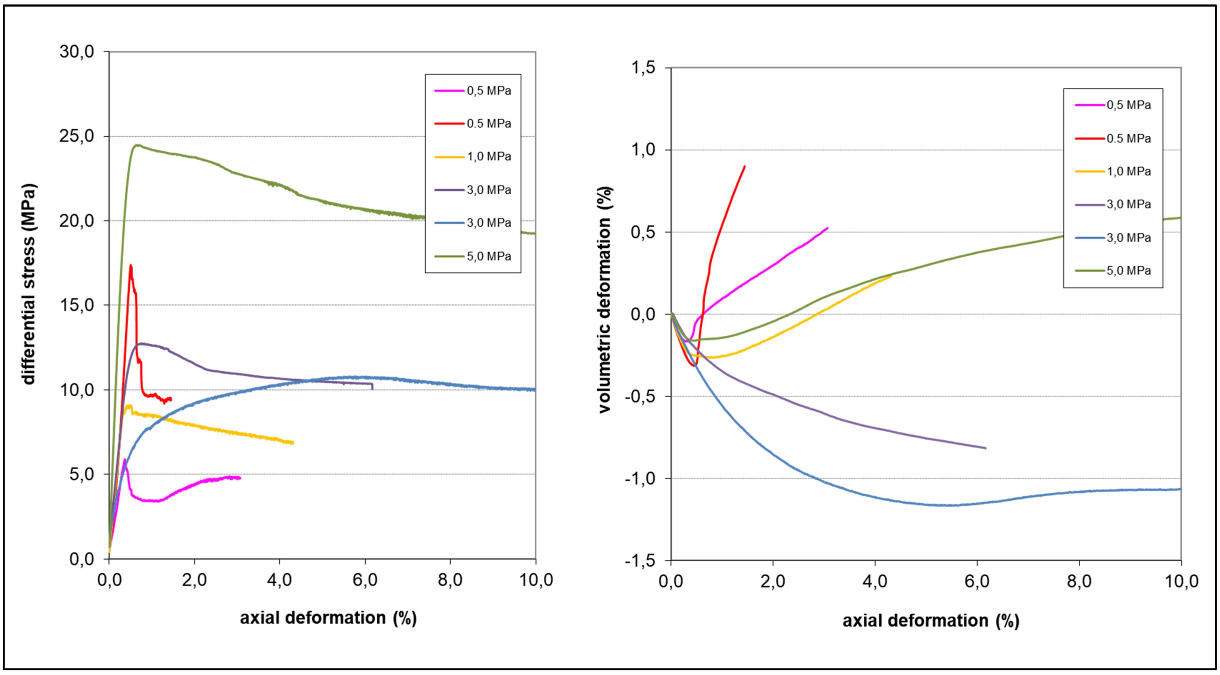


Fig. 4-3: *<u>Left:</u> stress-strain-diagram and <u>Right:</u> dilatancy-strain-diagram of the limestone samples from the MOS formation (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 5 MPa).*

As to be seen in Appendix 33, the strength depend on the confinement is well approximated by a linear fit in the range of $\sigma_3 \leq 5$ MPa (no curved strength boundary).

In a first approach the Mohr-Coulomb-approach (linear fit) was used, whereby based on the triaxial test results (for σ_3 = 0.2 to 5 MPa) the respective MOHR-COULOMB-parameters for the peak strength values are:

ϕ – friction angle: 33.2°

c – cohesion: 2.2 MPa

Here, especially the cohesion is higher than that of MAG and MAR samples.

The elastic parameters are shown in Appendix 36.

4.4 MRT – Marituba II

Between 269 and 283 m drilling depth, sandstones were extracted which were visually similar to the MAR formation samples. Those belong to the Marituba II formation (MRT).

Again, the fine-grained consolidated sandstones looked very homogenous and had no laminations, beddings, joints or other variations regarding mineral content or orientation (see photo-documentation in Appendix 45.

The samples of MRT had – as expected – a similar density compared to the MAR samples. The bulk density was ca. 2.15 g/cm³. No ultrasonic measurements were possible.

Four samples were prepared and tested to investigate the strength and deformation behaviour by performing triaxial compression strength tests (TC_nat). The strength tests were carried out at confining pressures of $0.5 \leq \sigma_3 \leq 5.0$ MPa with a constant deformation rate as given before.

The single results of the each TC-test are given in the Appendices 50–53 in the known form of a stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1) . The test conditions and peak strengths data are given in the table below (Table 4-4).

Tab. 4-4: *Strength and deformation parameters of triaxially tested Marituba II (MRT) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/MRT005/ TC_d1**	**743/MRT006/ TC_d2**	**743/MRT007/ TC_d3**	**743/MRT008/ TC_d4**
Formation	**MRT**	**MRT**	**MRT**	**MRT**
Sample	**MRT_005**	**MRT_006**	**MRT_007**	**MRT_008**
Length l (mm)	188.060	198.568	189.383	185.910
Diameter d (mm)	99.393	99.892	99.157	99.442
Ratio l_o/d_o	1.89	1.99	1.91	1.87
Mass M (g)	3286.60	3413.5	3070.5	2981.2
Area A (cm²)	77.589	78.370	77.221	77.666
Volume V (cm³)	1459.14	1556.18	1462.44	1443.88
Density ρ (g/cm³)	2.252	2.194	2.100	2.065

Temp. (°C)	23	23	23	23
σ_3 (MPa)	0.5	1.0	3.0	5.0
σ_{Dil} (MPa)	4.1	4.6	8.0	12.0
ΔV_{Dil} (%)	-0.27	-0.39	-0.53	-2.20
ε_{Dil} (%)	0.59	0.92	2.54	12.90
σ_{Fail} (MPa)	5.3	6.0	8.2	12.2
ΔV_{Fail} (%)	0.15	0.06	-0.45	-2.19
ε_{Fail} (%)	1.63	2.28	5.36	12.53
σ_{1Fail} (MPa)	5.80	6.98	11.19	17.19
Fracture type	B	B	D	D
E_{50} (GPa)	0.97	0.73	1.50	1.67
ν_{50}	0.26	0.31	0.39	0.38
K_{50} (GPa)	0.68	0.65	2.32	2.25
G_{50} (GPa)	0.39	0.28	0.54	0.61

Figure 4-4 gives a summarised overview about the progress of the four triaxial tests. The stress-strain-behaviour and even the failure development were similar to the MAR samples. No obvious decrease of the load-bearing capacity could be detected in tests with confinements higher than ≥ 3 MPa. The higher confining stresses (3 MPa and 5 MPa) also lead to sample deformation without visible fractures and (almost) no dilatancy. In particular, the test at 5 MPa indicates a continuing compaction of residual porosity.

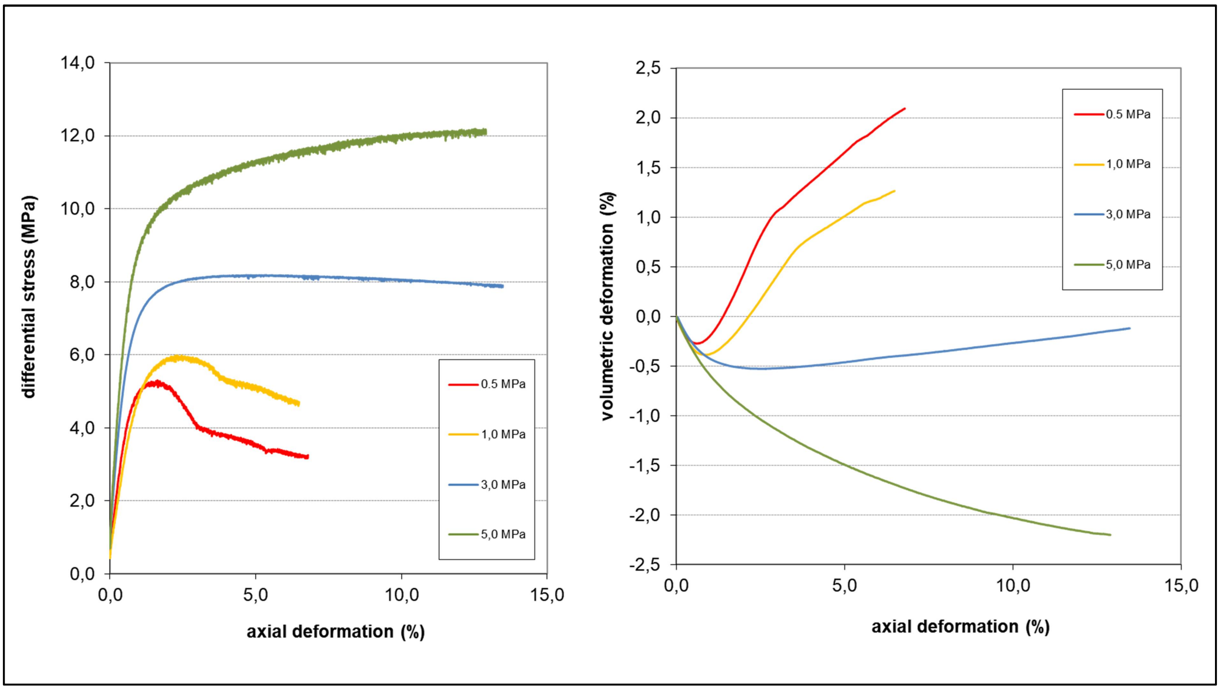


Fig. 4-4: *<u>Left:</u> stress-strain-diagram and <u>Right:</u> dilatancy-strain-diagram of the sandstone samples from the MRT formation (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 5 MPa).*

As seen in Appendix 46, the strength dependence on the confinement is linear in the range of $\sigma_3 \leq 5$ MPa (no curved strength boundary).

MOHR-COULOMB-parameters (resulting from the peak strength values) were :

ϕ – friction angle: 25.3°

c – cohesion: 1.4 MPa

They are comparable to those of the MAR samples.

The elastic parameters are shown in Appendix 49. Both Young's modulus and Poisson's ratio increase with confining stress.

4.5 IBU – Ibura Formation

From a depth of 311 m to 373 m cores of the Ibura Formation were drilled. 9 segments of them were available at IfG Leipzig and used for preparation of cylindrical specimens for triaxial tests.

Their compact habitus was evidently comparable to that of the Mosqueiro Formation. Both are limestones. The mean bulk density of the TC-test samples is 2.21 g/cm³. As to be seen in the photo-documentation in Appendix 56, the samples were homogenous without obvious beds or material changes or joints, etc.. Ultrasonic measurements were successful in only one sample (and there only in radial direction).

For comparison reasons the TC test were carried out again in the confining pressure range $0.5 \leq \sigma_3 \leq 5.0$ MPa.

The results of the individual tests are given in the Appendices 61–64 in the form of a stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1). The data of the peak strength values (and accordant strain values) are given in the table below (Table 4-5).

Tab. 4-5: *Strength and deformation parameters of triaxially tested Ibura limestone (IBU) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/IBU008/ TC_d1**	**743/IBU008/ TC_d2**	**743/IBU007/ TC_d3**	**743/IBU009/ TC_d4**
Formation	**IBU**	**IBU**	**IBU**	**IBU**
Sample	**IBU_008**	**IBU_008**	**IBU_007**	**IBU_009**
Length l (mm)	199.930	190.722	198.635	199.668
Diameter d (mm)	100.695	100.745	100.642	100.583
Ratio l_o/d_o	1.99	1.89	1.97	1.99
Mass M (g)	3436.90	3454.1	3645.9	3335.9

Area A (cm²)	79.635	79.714	79.552	79.458
Volume V (cm³)	1592.15	1520.33	1580.17	1586.53
Density ρ (g/cm³)	2.159	2.272	2.307	2.103
$V_{p\text{-axial}}$ (km/s)	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	-	-	-	3.53
$V_{p\text{-radial: b-d}}$ (km/s)	-	-	-	3.55
$V_{s\text{-axial}}$ (km/s)	-	-	-	-
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 **(MPa)**	0.5	1.0	3.0	5.0
σ_{Dil} **(MPa)**	23.8	22.5	21.0	21.8
ΔV_{Dil} **(%)**	-0.47	-0.33	-0.44	-1.88
ε_{Dil} **(%)**	0.74	0.56	0.78	6.76
σ_{Fail} **(MPa)**	24.9	22.6	22.0	23.6
ΔV_{Fail} **(%)**	-0.45	-0.33	-0.43	-0.26
ε_{Fail} **(%)**	0.85	0.56	0.68	0.38
σ_{1Fail} **(MPa)**	25.43	23.56	24.98	28.57
Fracture type	A	A	B	B/D
E_{50} **(GPa)**	3.33	5.21	4.27	12.37
ν_{50}	0.15	0.21	0.26	0.35
K_{50} **(GPa)**	1.57	3.00	2.95	13.44
G_{50} **(GPa)**	1.45	2.15	1.69	4.59

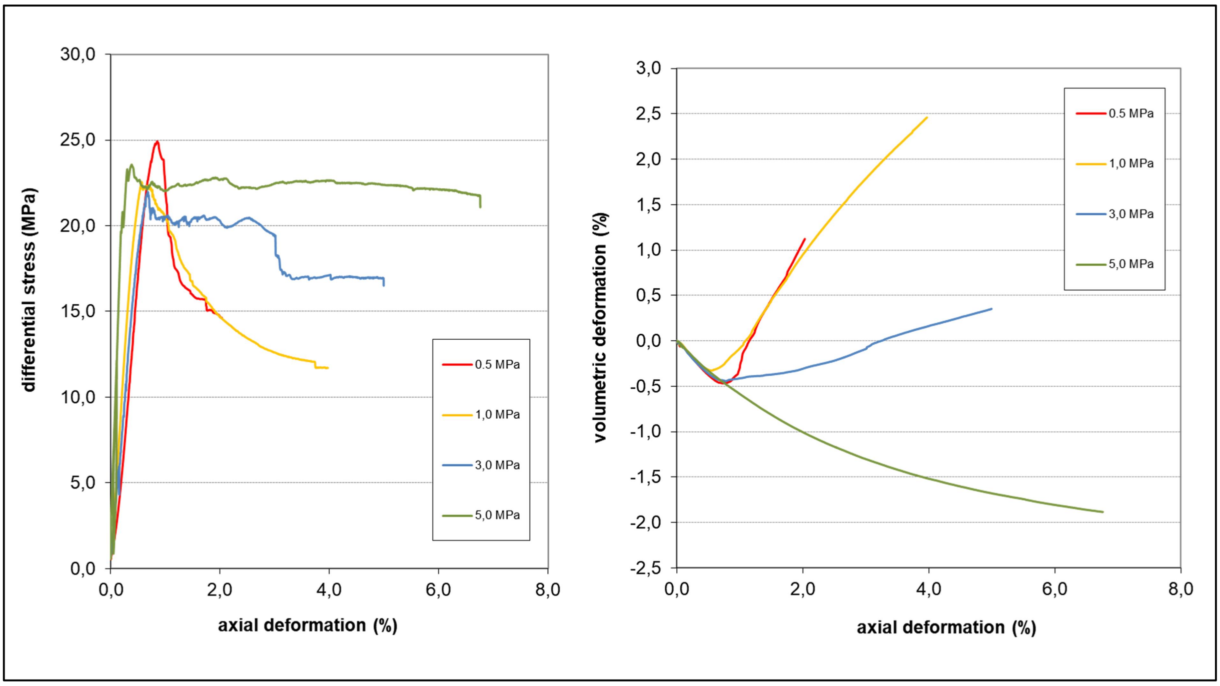


Fig. 4-5: *<u>Left:</u> stress-strain-diagram and <u>Right:</u> dilatancy-strain-diagram of the limestone samples from the IBU formation (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 5 MPa).*

Summarised results from the triaxial compression tests are represented in Figure 4-5. Here, the curves depict no clear dependency of the load bearing capacity at different confining pressures (σ_3). The depicted curves show an obvious scattering (in the low confinement range) which lead to the note, that definitely more tests have to be performed to investigate this behaviour. The peak strength values for all four confining pressure conditions are quite close to each other; only the post-failure range shows obvious variations. For smaller confining stresses, the failure is brittle, while at higher confining stress the samples behave more ductile in the post-failure range.

A linear Mohr-Coulomb-approach (based on the three triaxial test results (for $\sigma_3 = 1$ to 5 MPa)) results in:

ϕ – friction angle: 6.5°
c – cohesion: 9.8 MPa

The elastic parameters are shown in Appendix 60. Poisson's ratio increases with confining stress from 0.15 up to 0.4; Young's modulus is around 4 GPa except for the test at 5 MPa confining stress, which is considerably stiffer.

4.6 Poção Formation

In the stratigraphic well PE04, the Poção formation is encountered in the depth range from 376 m to 796 m. The formation contains several rock types, mostly sandstones, claystones, shales and conglomerates that are alternating repeatedly throughout the Poção formation.
Following the geological assessment of the drill core by Braskem and their team of experts, four lithological sub-units have been identified:

- PAR (sandstones) – overall length in PE04 240 m
- PCGL (conglomerates) – overall length in PE04 96 m
- PF (thinly intercalated dark shaly and calcilutitic)
- PI (thinly intercalated light arenitic, shaly, calcarenitic layers) –combined length of PI and PF in PE04 84 m

In the next sections, we discuss the lithological units in turn.

4.7 PAR – Poção Arenito

The PAR unit comprises relatively homogeneous grey sandstones without distinct intercalations or bedding planes (see Appendix 67 for sample photographs).
The average density was 1.93 g/cm^3; ultrasonic wave velocities could not be determined.

Five triaxial strength tests were performed at room temperature and confining stresses from 0.5 MPa to 10 MPa. The summaries and individual test data are given in the Appendices 72–76. Table 4-6 lists the key test parameters and peak values.

Tab. 4-6: *Strength and deformation parameters of triaxially tested Poção Arenito (PAR) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/PAR073/ TC_d1**	**743/PAR072/ TC_d2**	**743/PAR071/ TC_d3**	**743/PAR067/ TC_d6**	**743/PAR079/ TC_d7**
Formation	**PAR**	**PAR**	**PAR**	**PAR**	**PAR**
Sample	**PAR_073**	**PAR_072**	**PAR_071**	**PAR_067**	**PAR_079**
Length l (mm)	192.913	198.878	197.470	197.670	199.305
Diameter d (mm)	100,920	100,925	100,973	100,910	100,855
Ratio l_o/d_o	1.91	1.97	1.96	1.96	1.98
Mass M (g)	3017.60	3069.9	3030.7	3079.7	3028.5
Area A (cm²)	79.992	80.000	80.076	79.976	79.889
Volume V (cm³)	1543.14	1591.01	1581.25	1580.88	1592.22
Density ρ (g/cm^3)	1.955	1.930	1.917	1.948	1.902
$V_{p\text{-axial}}$ (km/s)	**-**	**-**	**-**	-	
$V_{p\text{-radial: a-c}}$ (km/s)	**-**	**-**	**-**	-	
$V_{p\text{-radial: b-d}}$ (km/s)	**-**	**-**	**-**	-	
$V_{s\text{-axial}}$ (km/s)	**-**	**-**	**-**	-	
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 **(MPa)**	0.5	1.0	2.0	5.0	10.0
σ_{Dil} **(MPa)**	6.0	7.0	9.8	13.4	18.4
ΔV_{Dil} **(%)**	-0.55	-0.64	-0.75	-1.62	-4.78
ε_{Dil} **(%)**	0.92	1.05	1.36	9.10	9.05
σ_{Fail} **(MPa)**	6.8	7.5	10.3	15.8	18.4
ΔV_{Fail} **(%)**	-0.45	-0.58	-0.74	-0.70	-4.78
ε_{Fail} **(%)**	1.15	1.25	1.52	1.33	9.04
σ_{1Fail} **(MPa)**	7.30	8.49	12.26	20.77	28.37
Fracture type	E	C	C	C	C
E_{50} **(GPa)**	0.68	0.74	0.88	2.14	3.74
ν_{50}	0.22	0.25	0.30	0.35	0.39
K_{50} **(GPa)**	0.40	0.49	0.74	2.34	5.74
G_{50} **(GPa)**	0.28	0.30	0.34	0.79	1.34

In Figure 4-6 we have collected the curves of differential stress and volumetric strain as function of the axial deformation for all tests.

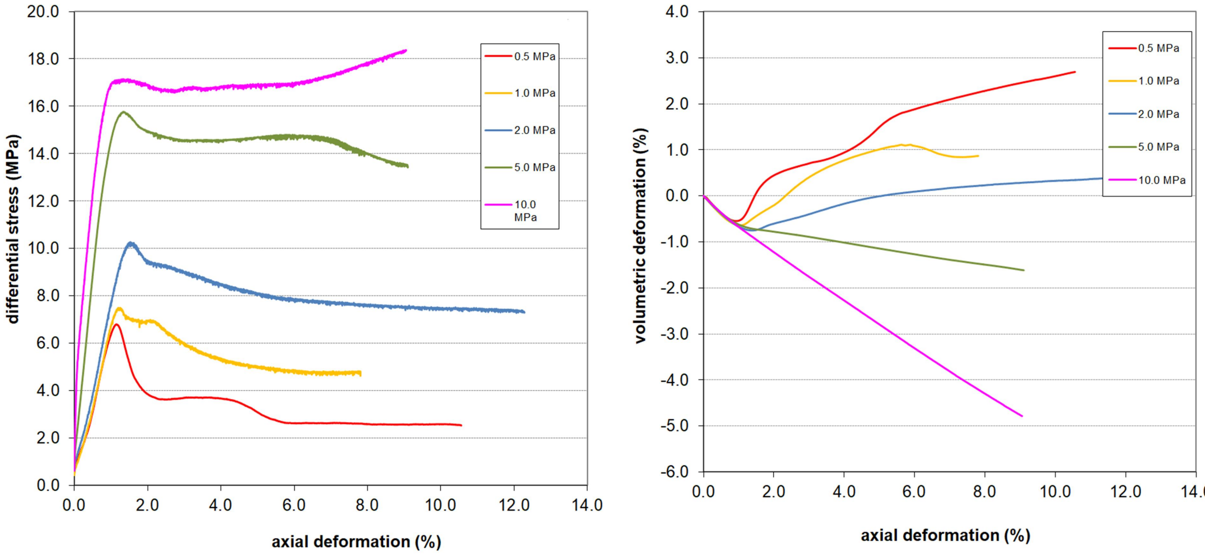


Fig. 4-6: *Left: stress-strain-diagram and Right: dilatancy-strain-diagram of the Poção Arenito lithological unit (PAR) (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 10 MPa).*

The material shows a comparatively plastic and ductile behaviour with only little softening after the peak and a comparatively large residual strength up to axial strains of more than eight percent. The fractures (Appendix 67) are mostly horizontal; the tests at 0.5 MPa and 2 MPa caused a stronger disintegration of parts of the sample. Note that the horizontal fracture mode and ductile plastic behaviour is associated with rather small post-failure dilatancy, or even continuing compaction. This indicates that residual porosity is reduced during the tests.

A linear Mohr-Coulomb analysis of the peak strengths leads to the following values:

ϕ – friction angle: 22.5°

c – cohesion: 2.4 MPa

The following dynamic elastic moduli were determined:

E – Young’s modulus: 6.4 GPa

ν – Poisson’s ratio: 0.21

The static elastic moduli are shown in Appendix 71. Both E_{50} and ν_{50} increase with confining stress.

4.8 PCGL – Poção Conglomerado

The Poção formation contains several layers of conglomerates that are collected in the PCGL unit. The conglomerates are composed of a homogeneous grey sandstone matrix

(similar to the PAR unit) with generally well-rounded clasts with diameters form several centimetres to several decimetres. The clast density varies strongly, and the available cores contain several clast-free pieces of at least one metre in length. Besides the clasts, there we no obvious inhomogeneities, bedding planes etc.
To assess the influence of both clasts and matrix on the strength behaviour, five triaxial tests were performed on pure matrix samples (i.e. essentially without any visible clasts; Appendices 79–88), and four test used samples with clasts (Appendices 89-98). Samples with clasts were chosen such that no clasts spanned the entire length of the sample (see Appendix 91 for sample photographs).

Table 4-7 collects the test parameters and peak values. The average sample density is higher than for PAR with 2.01 g/cm^3, possibly due to small clasts contained in the samples. Correspondingly, the samples with clasts (Table 4-8) show significantly higher densities, with an average of 2.38 g/cm^3. Ultrasonic wave velocities could not be determined expect for one matrix sample.

Tab. 4-7: *Strength and deformation parameters of triaxially tested Poção conglomerate (PCGL) samples without clasts. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	743/PCGL050/TC_d1	743/PCGL049/TC_d2	743/PCGL048/TC_d3	743/PCGL045/TC_d4	743/PCGL046/TC_d5
Formation	**PCGL**	**PCGL**	**PCGL**	**PCGL**	**PCGL**
Sample	**PCGL_050**	**PCGL_049**	**PCGL_048**	**PCGL_045**	**PCGL_046**
Length l (mm)	200.163	199.963	199.568	198.505	198.035
Diameter d (mm)	100,730	100,673	100,700	100,682	100,698
Ratio l_o/d_o	1.99	1.99	1.98	1.97	1.97
Mass M (g)	3187.90	3187.4	3186.8	3202.3	3202.4
Area A (cm²)	79.691	79.601	79.643	79.615	79.640
Volume V (cm³)	1595.11	1591.72	1589.42	1580.39	1577.15
Density ρ (g/cm^3)	1.999	2.002	2.005	2.026	2.030
$V_{p\text{-axial}}$ (km/s)	-	-	-	-	
$V_{p\text{-radial: a-c}}$ (km/s)	-	-	38.53	-	
$V_{p\text{-radial: b-d}}$ (km/s)	-	-	-	-	
$V_{s\text{-axial}}$ (km/s)	-	-	-	-	
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 **(MPa)**	0.5	1.0	2.0	5.0	10.0
σ_{Dil} **(MPa)**	7.1	9.6	12.1	13.4	20.7

ΔV_{Dil} (%)	-0.43	-0.56	-0.42	-1.63	-4.80
ε_{Dil} (%)	0.68	0.78	0.71	7.21	9.99
σ_{Fail} (MPa)	7.9	10.2	12.6	15.2	20.7
ΔV_{Fail} (%)	-0.30	-0.52	-0.38	-0.54	-4.78
ε_{Fail} (%)	0.86	0.90	0.84	0.85	9.95
σ_{1Fail} (MPa)	8.38	11.17	14.63	20.16	30.69
Fracture type	B	B	C	D	C
E_{50} (GPa)	1.10	1.36	1.96	2.80	4.27
ν_{50}	0.19	0.17	0.28	0.34	0.37
K_{50} (GPa)	0.59	0.70	1.46	2.91	5.42
G_{50} (GPa)	0.46	0.58	0.77	1.05	1.56

Tab. 4-8: *Strength and deformation parameters of triaxially tested Poção conglomerate (PCGL) samples with clasts. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/PCGL060/ TC_d6**	**743/PCGL059/ TC_d7**	**743/PCGL058/ TC_d8**	**743/PCGL057/ TC_d9**
Formation	**PCGL**	**PCGL**	**PCGL**	**PCGL**
Sample	**PCGL_060**	**PCGL_059**	**PCGL_058**	**PCGL_057**
Length l (mm)	203.655	199.608	200.493	170.685
Diameter d (mm)	100,493	100,672	100,643	100,663
Ratio l_o/d_o	2.03	1.98	1.99	1.70
Mass M (g)	3710.3	3798.7	3848.6	3278.2
Area A (cm²)	79.316	79.599	79.553	79.585
Volume V (cm³)	1615.31	1588.86	1594.98	1358.39
Density ρ (g/cm^3)	2.297	2.391	2.413	2.413
$V_{p\text{-axial}}$ (km/s)	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	-	-	-	3,53
$V_{p\text{-radial: b-d}}$ (km/s)	-	-	-	3,55
$V_{s\text{-axial}}$ (km/s)	-	-	-	-
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 (MPa)	0.5	2.0	5.0	10.0
σ_{Dil} (MPa)	7.0	10.8	24.0	10.9
ΔV_{Dil} (%)	-0.13	-0.15	-0.16	-0.14
ε_{Dil} (%)	0.22	0.29	0.28	4.54
σ_{Fail} (MPa)	7.8	12.3	24.5	18.6
ΔV_{Fail} (%)	-0.10	0.36	-0.14	-0.06
ε_{Fail} (%)	0.28	10.50	0.71	0.31
σ_{1Fail} (MPa)	8.26	14.27	29.47	28.64
Fracture type	B/E	B/E	C	E

E_{50} (GPa)	2.95	5.52	12.43	9.66
ν_{50}	0.25	0.27	0.28	0.46
K_{50} (GPa)	1.94	3.93	9.51	45.56
G_{50} (GPa)	1.18	2.18	4.85	3.30

The strength behaviour, on the other hand is similar within the expected experimental scatter, as seen in Figure 4-7. The samples with clasts are systematically stiffer, but the peak and residual strengths are in the same range.

The failure pattern in the matrix samples (Appendix 79) shows mostly horizontal and some diagonal shear fractures; the samples with clasts failed in the matrix or along the matrix-clast interfaces (Appendix 91).

Overall, the tests show that the clasts are much stronger and stiffer than the matrix, but the strength of the rock mass is determined by the matrix and interfaces.

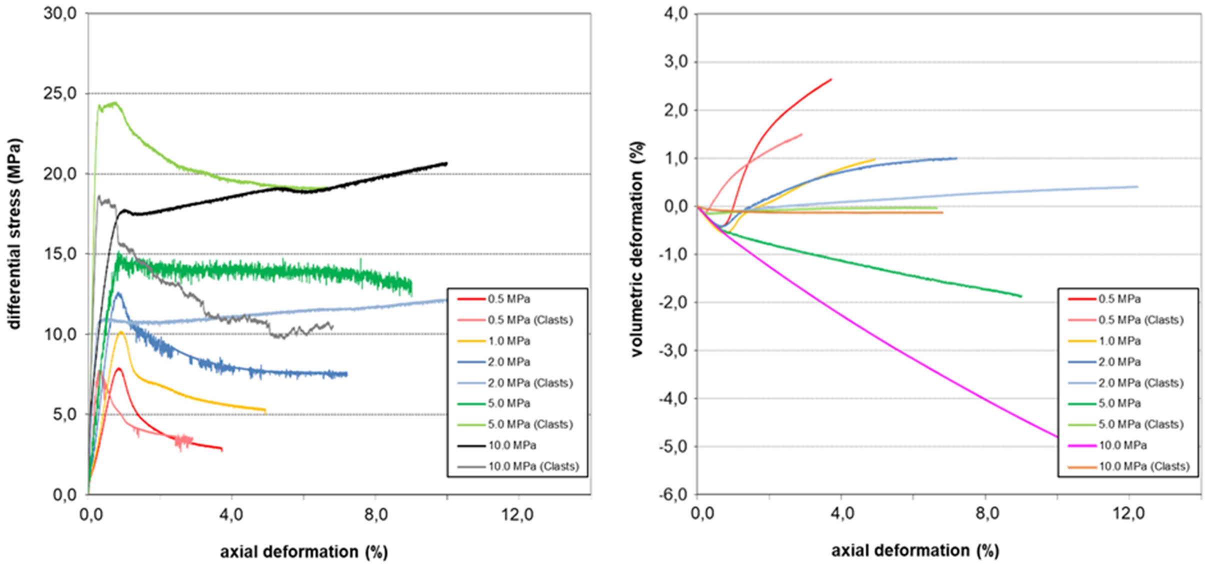


Fig. 4-7: *<u>Left:</u> stress-strain-diagram and <u>Right:</u> dilatancy-strain-diagram of the Poção conglomerates lithological unit (PCGL) (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 10 MPa; samples with matrix only and with clasts tested separately).*

The linear Mohr-Coulomb analysis of the peak strengths leads to the following values for the matrix:

ϕ – friction angle: 22.4°

c – cohesion: 2.9 MPa

The samples with clasts give similar strengths:

ϕ – friction angle: 21.5°

c – cohesion: 3.7 MPa

The following dynamic elastic moduli were determined:

E – Young's modulus: 8.2 GPa

ν – Poisson's ratio: 0.31

The static elastic moduli are shown in Appendix 83. As for most other lithological units, E_{50} and ν_{50} generally increase with confining stress, with Poisson's ratio exceeding 0.4 at high σ_3. The samples with clasts are consistently stiffer than the pure-matrix samples, while Poisson's ratio does not show a significant trend. This, together with the strength results, indicates that the clasts are significantly stronger and stiffer than the matrix, and the mechanical behaviour is dominated by the matrix.

4.9 PI – Poção Intercalado

The PI unit consists of grey sandstones with interspersed subhorizontal dark and light grey (shaly and calcarenitic) layers.

Four samples were prepared for triaxial strength tests with confining pressures from 0.5 MPa to 5 MPa (see Table 4-9 and Appendices 99 – 109). Average density was 1.93 g/cm^3, similar to the sandstone samples from PAR. Ultrasonic wave velocities could not be determined.

Tab. 4-9: *Strength and deformation parameters of triaxially tested Poção Intercalado (PI) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/PI001/TC_ d1**	**743/PI002/TC_ d2**	**743/PI003/TC_ d3**	**743/PI006/TC_ d4**
Formation	**PI**	**PI**	**PI**	**PI**
Sample	**PI_001**	**PI_002**	**PI_003**	**PI_006**
Length l (mm)	198.105	200.375	198.268	198.920
Diameter d (mm)	99,798	100,197	99,557	99,053
Ratio l_o/d_o	1.99	2.00	1.99	2.01
Mass M (g)	3036.80	3123.7	2845.6	2967.1
Area A (cm²)	78.223	78.850	77.845	77.059
Volume V (cm³)	1549.63	1579.95	1543.43	1532.86
Density ρ (g/cm^3)	1.960	1.977	1.844	1.936
$V_{p\text{-axial}}$ (km/s)	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s)	-	-	-	-
$V_{s\text{-axial}}$ (km/s)	-	-	-	-
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 **(MPa)**	0.5	1.0	2.0	5.0
σ_{Dil} **(MPa)**	5.4	6.9	10.6	12.2
ΔV_{Dil} **(%)**	-0.27	-0.29	-0.32	-1.75
ε_{Dil} **(%)**	0.50	0.45	0.63	5.46
σ_{Fail} **(MPa)**	6.4	8.8	11.8	15.2
ΔV_{Fail} **(%)**	-0.12	-0.19	-0.27	-0.50

ε_{Fail} **(%)**	0.79	0.67	0.81	0.92
σ_{1Fail} **(MPa)**	6.94	9.78	13.83	20.24
Fracture type	B	B	B/C	C
E_{50} **(GPa)**	1.14	1.59	1.96	2.90
ν_{50}	0.26	0.25	0.32	0.34
K_{50} **(GPa)**	0.78	1.05	1.78	3.11
G_{50} **(GPa)**	0.45	0.64	0.74	1.08

In Figure 4-8 we have collected the curves of differential stress and volumetric strain as function of the axial deformation for all tests. The samples are less ductile than the PAR and PCGL samples, with a clear drop in strength after the peak. However, there is a considerable strength plateau. The failure (Appendix 101) occurs by diagonal shear fracture for smaller confining stress and horizontal fractures for larger σ_3. Again, for higher confining stresses, the horizontal fractures are associated with essentially no post-failure dilatancy.

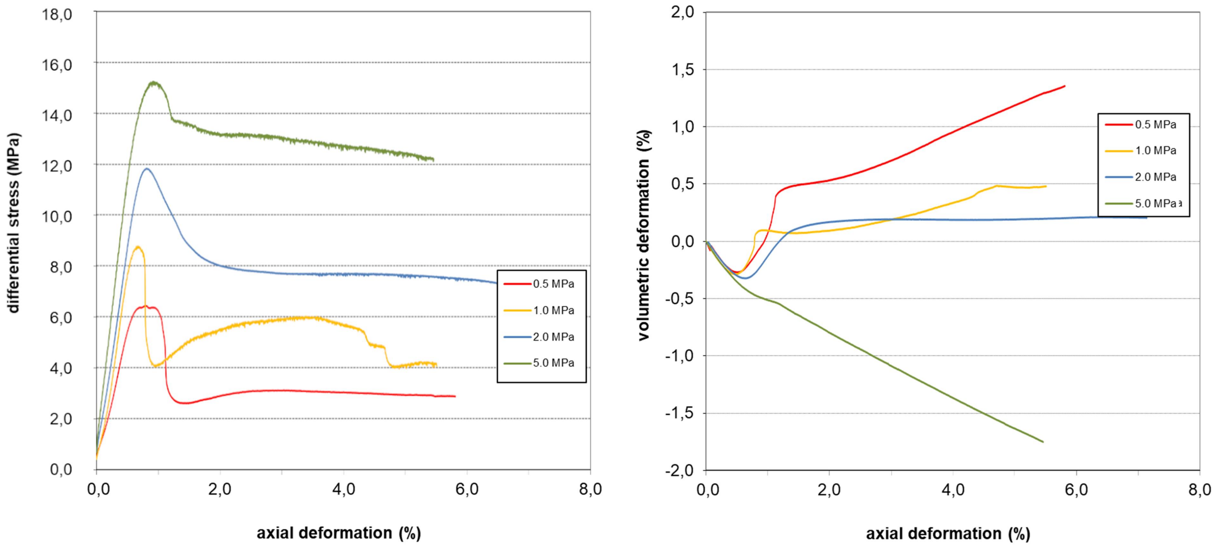


Fig. 4-8: *Left: stress-strain-diagram and Right: dilatancy-strain-diagram of the Poção Intercalado lithological unit (PI) (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 5 MPa).*

The regression of Mohr-Coulomb parameters (Appendix 102) leads to the following (peak strength) values:

ϕ – friction angle: 28.3°

c – cohesion: 2.0 MPa

The elastic moduli (Appendix ´105) show a small dependence on the confining stress and are similar to the PAR and PCGL matrix samples.

4.10 PF – Poção Folhelho

The PF unit consists of mostly dark grey shales with subhorizontal bedding and some dark or light grey intercalations.

Five samples were triaxially tested with confining pressures from 0.5 Pa to 10 MPa; additionally, four direct shear tests were performed (Appendices 110 – 128).
Table 4-10 lists the parameters of the TC tests. Average sample density was 1.87 g/cm^3, lower than the other Poção units. Ultrasonic wave velocities could be determined only for two samples (axial p-waves).

Tab. 4-10: *Strength and deformation parameters of triaxially tested Poção Folhelho (PF) samples. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/PF032/TC_d1**	**743/PF033/TC_d2**	**743/PF033/TC_d3**	**743/PF034/TC_d4**	**743/PF035/TC_d5**
Formation	**PF**	**PF**	**PF**	**PF**	**PF**
Sample	**PF_032**	**PF_033**	**PF_033**	**PF_034**	**PF_035**
Length l (mm)	200.703	199.640	200.123	199.288	199.655
Diameter d (mm)	101,138	101,230	100,908	100,833	100,530
Ratio l_o/d_o	1.98	1.97	1.98	1.98	1.99
Mass M (g)	3099.90	2985.0	2962.0	2956.0	2981.9
Area A (cm²)	80.338	80.484	79.973	79.854	79.375
Volume V (cm³)	1612.40	1606.78	1600.44	1591.39	1584.75
Density ρ (g/cm^3)	1.923	1.858	1.851	1.857	1.882
$V_{p\text{-axial}}$ (km/s)	-	-	-	-	
$V_{p\text{-radial: a-c}}$ (km/s)	2.51	-	-	-	2.54
$V_{p\text{-radial: b-d}}$ (km/s)	-	-	-	-	2.58
$V_{s\text{-axial}}$ (km/s)	-	-	-	-	
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 **(MPa)**	0.5	1.0	2.0	5.0	10.0
σ_{Dil} **(MPa)**	10.2	9.6	14.3	13.5	13.5
ΔV_{Dil} **(%)**	-0.25	-0.38	-0.34	-1.50	-0.27
ε_{Dil} **(%)**	0.45	0.58	0.60	5.29	1.73
σ_{Fail} **(MPa)**	10.9	9.9	14.3	16.0	16.0
ΔV_{Fail} **(%)**	-0.23	-0.38	-0.34	-0.47	0.52
ε_{Fail} **(%)**	0.53	0.62	0.62	0.82	6.07
σ_{1Fail} **(MPa)**	11.38	10.86	16.33	21.02	26.01
Fracture type	A/B	B	B	D	D
E_{50} **(GPa)**	2.56	1.99	3.12	3.01	5.56
ν_{50}	0.21	0.18	0.27	0.37	0.48

K_{50} (GPa)	1.46	1.03	2.23	3.94	54.61
G_{50} (GPa)	1.06	0.84	1.23	1.10	1.87

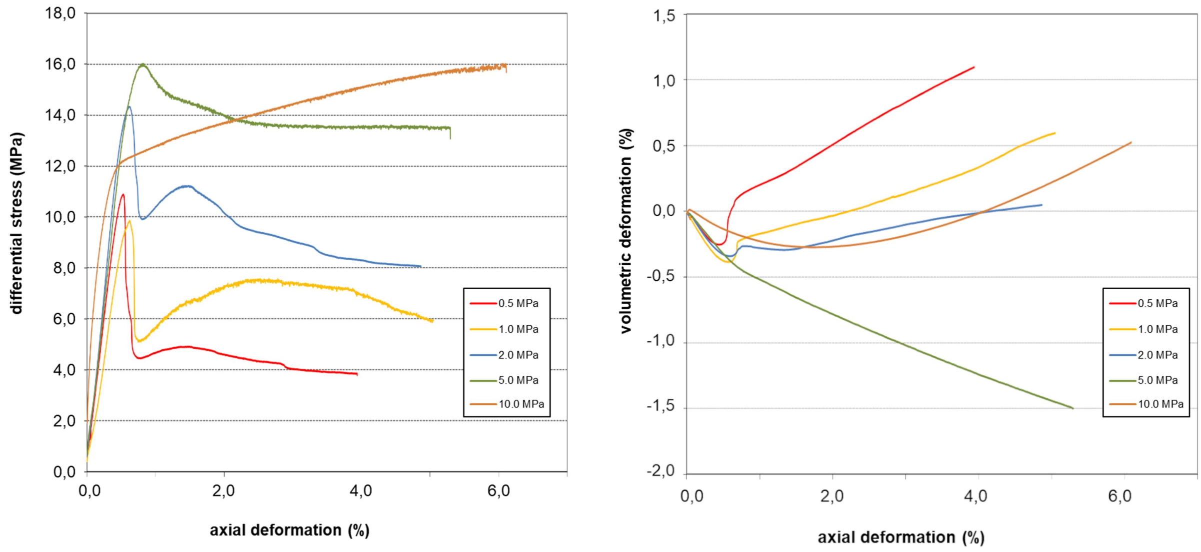


Fig. 4-9: *<u>Left:</u> stress-strain-diagram and <u>Right:</u> dilatancy-strain-diagram of the Poção Folhelho lithological unit (PF) (short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 10 MPa).*

The TC tests (see Figure 4-9) show a clear brittle-ductile transition, with large stress drops in the post-failure regime for smaller confining stresses and no peak at all, i.e. continuing hardening, for 10 MPa of lateral stress. Correspondingly, there is not dilatancy for the highest confining stress, while there is an obvious jump in dilatancy at failure for the lower values of σ_3. The failure modes (Appendix 112) show diagonal shear fractures for 0.5 MPa to 2 MPa and no visible cracks for 5 MPa and 10 MPa.

The Mohr-Coulomb parameters (Appendix 113) are:

ϕ – friction angle: 13.0°

c – cohesion: 4.5 MPa

The following dynamic elastic moduli were determined:

E – Young's modulus: 8.9 GPa

ν – Poisson's ratio: 0.14

The static elastic parameters (see Appendix 116) depend on the confining stress. Young's modulus increases from 2 GPa to 5.6 GPa; Poisson's ratio goes up to 0.48 for σ_3=10 MPa.

In addition, four PF samples were tested in direct shear tests. The tests were performed under constant normal load (CNL) conditions with normal stress of 0.5 to 6.0 MPa. Each test comprised two load stages, with a first load-stage to determine the peak shear and residual strength, and a second load stage to provide the residual strength.

Samples were chosen with conspicuous bedding planes or laminations (see Appendices 122 and 123).

From the σ_n-τ-diagram (Appendix 124; see also Table 4-11), the following Mohr-Coulomb parameters could be derived:

For the maximum shear strength values:

- Cohesion c = 2.0 MPa
- Angle of friction ϕ = 17°

For the residual shear strength values:

- Angle of friction ϕ = 24°

Tab. 4-11: *Summary of shear tests on Poção Folhelho (PF) samples*

Sample	Load step	shear parameter		for peak strength		for residual strength	
		σ_n	τ	c	ϕ	c	ϕ
		MPa	MPa	MPa	°	MPa	°
743/PF/SV1	1	0.50	1.70	2.0	17	0,00	24
	1	0.50	0.60				
	2	1.00	0.87				
743/PF/SV2	1	0.75	2.73				
	1	0.75	0.77				
	2	1.50	0.99				
743/PF/SV3	1	2.00	2.61				
	1	2.00	1.00				
	2	4.00	1.65				
743/PF/SV4	1	4.00	3.21				
	1	4.00	2.07				
	2	6.00	2.26				

4.11 TMS – Tabuleiro

Due to the expected importance of this unit, one of the major foci was on the investigations of material from the Tabuleiro Formation /TMS). Here, besides triaxial tests under natural humidity conditions, triaxial tests with applied pore pressures and tests of partially saturated samples were performed as well. Further, testing of the bedding planes of the occurring shales were done with direct tensile strength tests, splitting tests as well as direct shear tests.

The shale samples of the TMS came from a depth of 812 to 903 m. They represent a very compact rock type with obvious lamination (moderate to steeply dipping) in nearly all samples. Some of them failed along these bedding planes even before preparation. This indicated that these bedding planes act as potential weakness planes.

The bulk density of the selected core material was 2.29 g/cm³ (mean value), ranging from 2.1 to 2.4 g/cm³. Ultrasonic measurements were only possible in radial direction of the samples (v_P = 3.4 km/s), the axial signal was strongly cushioned by the laminated rocks and no values could be determined.

The TC tests were carried out in a wide confining pressure range of $0.2 \leq \sigma_3 \leq 16.0$ MPa. Therefore, a well overview about the stress-strain behaviour of TMS-shales can be given.

The results of the individual tests are given in Appendices 137–145 in the form of stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1) diagrams. The data of the peak strength (and accordant strain) are given in the table below (Table 4-12).

Tab. 4-12a: *Strength and deformation parameters of triaxially tested TMS shales. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/005/ TC_d1**	**743/027/ TC_d2**	**743/046/ TC_d3**	**743/054/ TC_d4**	**743/116/ TC_d5**
Formation	**TMS**	**TMS**	**TMS**	**TMS**	**TMS**
Sample	**TMS-005**	**TMS-027**	**TMS-046**	**TMS-054**	**TMS-116**
Length l (mm)	199.592	199.925	200.715	199.748	199.145
Diameter d (mm)	100.520	100.460	100.067	99.992	99.227
Ratio l_o/d_o	1.99	1.99	2.01	2.00	2.01
Mass M (g)	3727.20	3847.2	3720.1	3668.9	3353.4
Area A (cm²)	79.359	79.264	78.645	78.527	77.330
Volume V (cm³)	1583.94	1584.69	1578.53	1568.57	1539.99
Density ρ (g/cm³)	2.353	2.428	2.357	2.339	2.178
$V_{p\text{-axial}}$ (km/s)	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	3.27	3.53	3.32	2.75	-
$V_{p\text{-radial: b-d}}$ (km/s)	3.29	3.90	3.39	3.69	-
$V_{s\text{-axial}}$ (km/s)	-	-	-	-	-
Temp. (°C)	23	23	23	23	23
σ_3 (MPa)	0.2	0.5	1.0	3.0	5.0
σ_{Dil} (MPa)	20.2	11.7	18.9	20.4	24.2
ΔV_{Dil} (%)	-0.52	-0.35	-0.48	-0.34	-0.39
ε_{Dil} (%)	0.65	0.57	0.76	0.71	0.83
σ_{Fail} (MPa)	20.2	12.5	19.1	20.5	27.1
ΔV_{Fail} (%)	-0.52	-0.33	-0.48	-0.34	-0.31
ε_{Fail} (%)	0.65	0.67	0.77	0.72	1.23

σ_{1Fail} (MPa)	20.37	12.97	20.14	23.55	32.13
Fracture type	A	A	B/A	B	B
E_{50} (GPa)	2.65	2.16	2.46	3.60	3.44
v_{50}	0.06	0.16	0.17	0.34	0.33
K_{50} (GPa)	1.00	1.07	1.23	3.87	3.41
G_{50} (GPa)	1.26	0.93	1.06	1.34	1.29

Tab. 4-12b: Strength and deformation parameters of triaxially tested TMS shales (continued).

IfG - Lab-No.	743/103/TC_d 6	743/112/TC_d 7	743/014/TC_d 8	743/082/TC_d 9
Formation	**TMS**	**TMS**	**TMS**	**TMS**
Sample	**TMS-103**	**TMS-112**	**TMS-014**	**TMS-082**
Length l (mm)	201.020	198.633	200.390	195.568
Diameter d (mm)	101.135	99.123	100.315	101.01
Ratio l_o/d_o	1.99	2.00	2.00	1.94
Mass M (g)	3741.8	3227.4	3809.9	3388.1
Area A (cm²)	80.333	77.168	79.035	80.134
Volume V (cm³)	1614.85	1532.82	1583.79	1567.17
Density ρ (g/cm^3)	2.317	2.106	2.406	2.162
$V_{p\text{-axial}}$ (km/s)	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	3.19	-	3.96	3.19
$V_{p\text{-radial: b-d}}$ (km/s)	-	-	4.12	-
$V_{s\text{-axial}}$ (km/s)	-	-	-	-
Temp. (°C)	23	23	23	23
σ_3 **(MPa)**	10.0	16.0	7.5	12.5
σ_{Dil} **(MPa)**	23.8	23.8	61.4	31.5
ΔV_{Dil} **(%)**	-0.51	-1.45	-0.35	-0.75
ε_{Dil} **(%)**	0.81	10.94	0.59	1.43
σ_{Fail} **(MPa)**	23.8	27.5	64.1	32.4
ΔV_{Fail} **(%)**	-0.51	-1.16	-0.33	-0.74
ε_{Fail} **(%)**	0.81	2.96	0.69	1.31
σ_{1Fail} **(MPa)**	33.75	43.54	71.63	44.91
Fracture type	B*	B/D	B	B
E_{50} **(GPa)**	4.26	4.11	11.93	5.05
v_{50}	0.37	0.42	0.25	0.37
K_{50} **(GPa)**	5.49	8.25	8.03	6.43
G_{50} **(GPa)**	1.55	1.45	4.76	1.84

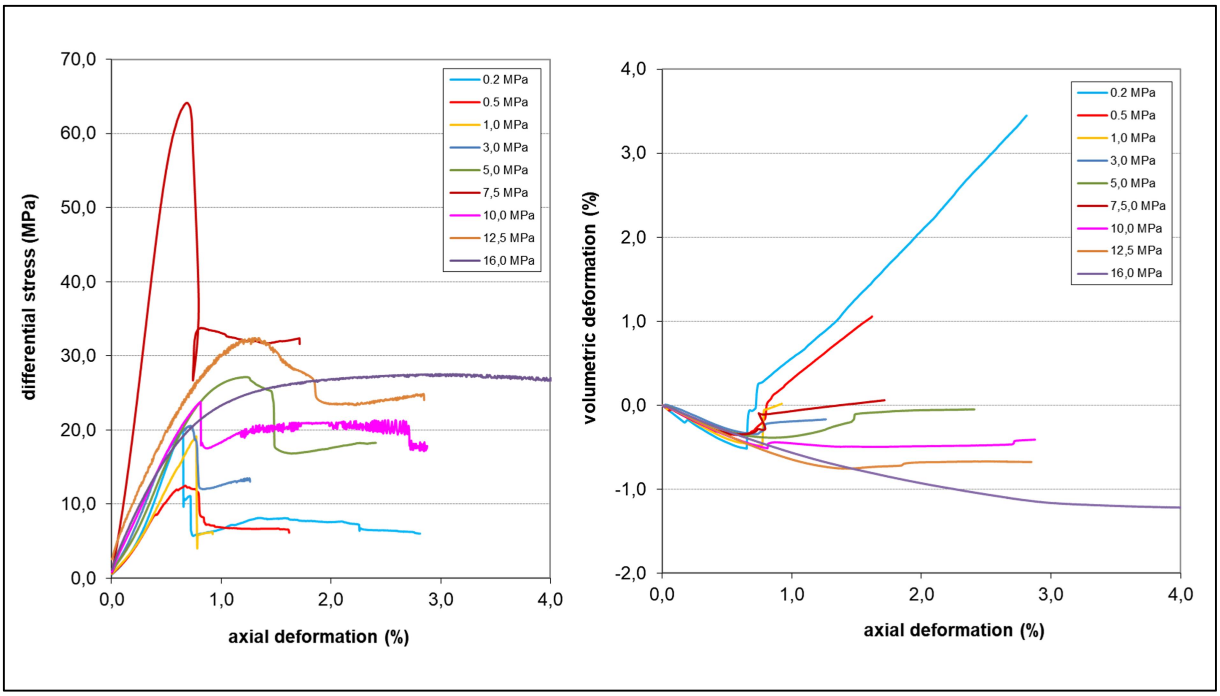


Fig. 4-10: *<u>Left:</u> stress-strain-diagram and <u>Right:</u> dilatancy-strain-diagram of the shale samples from the TMS formation (short-term triaxial compression tests with confining pressures of σ_3 = 0.2 to 16 MPa).*

Summarised results from the triaxial compression tests are represented in Figure 4-10. Here, the curves represent the typical behaviour of strongly consolidated shales. They depict the dependency of the load bearing capacity at different confining pressures (σ_3). The curves show a scattering (especially the test at 7.5 MPa is an outlier). All samples showed strong brittle behaviour with – after reaching the maximum stress level – an abrupt drop of the differential stress in the post-failure region. As to be seen in the photo-documentation (Appendices 131 and 132), nearly all specimens showed failure behaviour as to be known from uniaxial (unconfined) conditions. Vertical to steep dipping shear planes occurred even at high confining pressure conditions; only the 16 MPa test showed a more ductile behaviour with bulging of the sample, together with diagonal shear bands. Accordingly, at 16 MPa, there is no dilatancy in the post-failure region.

A linear Mohr-Coulomb-approach (based on the triaxial test results) leads to:

ϕ – friction angle: 19.5°

c – cohesion: 7.5 MPa

The dynamic elastic parameters were determined with:

E – Young's modulus: 6.5 (GPa)

ν – Poisson's ratio: 0.14

The static elastic parameters are shown in Appendix 136. The dependence of Young's modulus on confining stress is smaller than for the higher lithological units (except for an outlier at σ_3=7.5 MPa). Poisson's ratio is small for low confining stress and goes up to 0.42 for 16 MPa. (Elastic parameters were only determined for the TC_nat tests.)

As stated above, some samples were – in a first stage – tested under natural humidity conditions, and in the post-failure range an unloading-reloading cycle was processed under constant confining pressure conditions. But, in the reloading cycle an acting pore pressure (in the order of half of the confining pressure) was applied. The pore pressure was applied by using oil as an injection medium. The intension was to analyse, how is the influence to the already damaged sample and its residual strength, if a pore pressure acts. It was expected that the residual strength would be evidently reduced due to the reduction of cohesion. Therefore, 4 test in the confining pressure range of 1.0 ≤ σ_3 ≤ 10.0 MPa.

The results of the individual tests are given in the Appendices 149–152 in the form of stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1) diagrams. The data of the peak and residual strength and strains are given in the table below (Table 4-13).

Tab. 4-13: *Strength and deformation parameters of triaxially tested TMS shales with applied pore pressure. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	743/TMS005/ TC_w1_pp	743/TMS045/ TC_w2_pp	743/TMS044/ TC_w5_pp	743/TMS072/ TC_w8pp
Formation	**TMS**	**TMS**	**TMS**	**TMS**
Sample	**TMS-005**	**TMS-045**	**TMS-046**	**TMS-072**
Length l (mm)	200.553	184.090	201.003	191.950
Diameter d (mm)	100.60	100.09	99.488	100.41
Ratio l_o/d_o	1.99	1.84	2.02	1.91
Mass M (g)	4096.90	3307.2	3569.4	3465.7
Area A (cm^2)	79.485	78.681	77.738	79.185
Volume V (cm^3)	1594.10	1448.44	1562.55	1519.96
Density ρ (g/cm^3)	2.570	2.283	2.284	2.280
$V_{p\text{-axial}}$ (km/s)	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	6.09	3.21	-	2.98
$V_{p\text{-radial: b-d}}$ (km/s)	6.05	3.17	-	3.01
$V_{s\text{-axial}}$ (km/s)	-	-	-	-
Temp. (°C)	23	23	23	23
σ_3 **(MPa)**	1.0	3.0	10.0	7.0
pore pressure (MPa)	0.5	1.5	5.0	3.5
σ_{Dil} **(MPa)**				
ΔV_{Dil} **(%)**				
ε_{Dil} **(%)**				
σ_{Fail} **(MPa)**	16.94	22.16	28.20	24.92

ΔV_{Fail} (%)				
ε_{Fail} (%)	1.33	1.15	1.36	1.03
σ_{1Fail} (MPa)	17.94	25.16	38.20	31.92
$\sigma_{res,\ nat}$ (MPa)	13.98	13.40	26.82	20.17
$\sigma_{res,\ pore}$ (MPa)	12.79	11.99	26.55	19.37
Fracture type	C*	C*/B		B

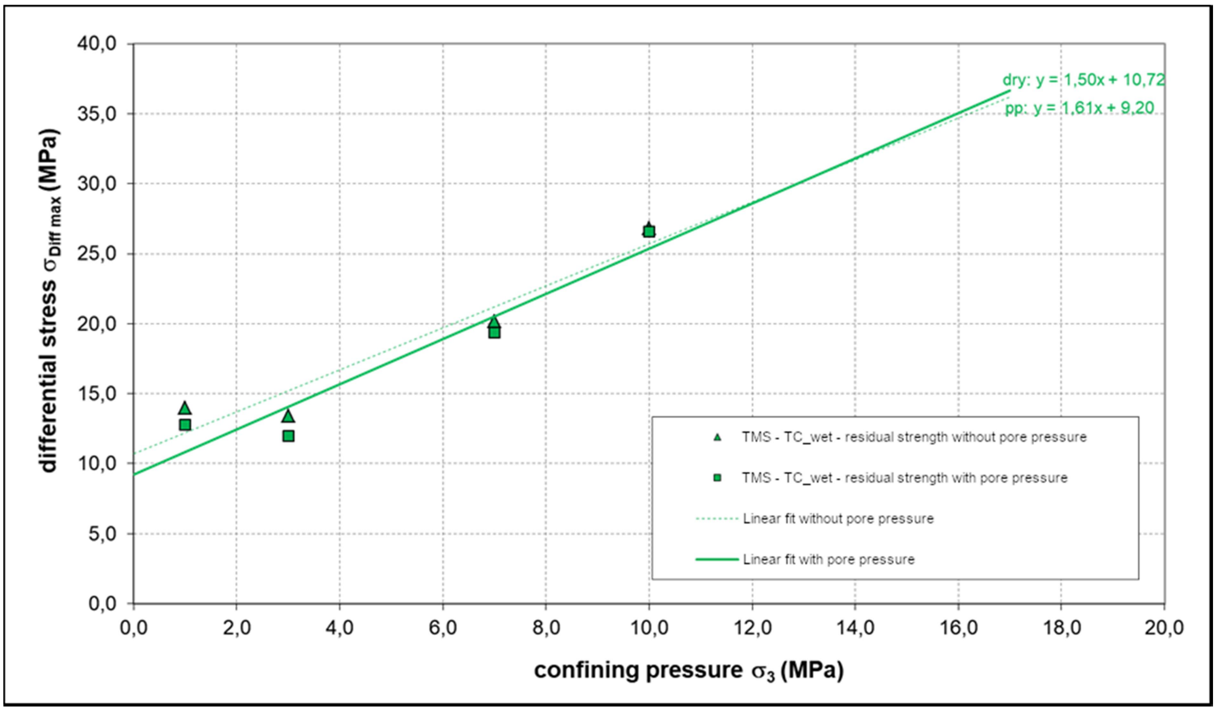


Fig. 4-11: *Comparison of the residual strength of natural-humidity samples (triangles) v those of samples with applied pore pressure (squares).*

As to be seen in the summarised diagram (Figure 4-11) as well as in the curves representing the single testing progress (see Appendices 133 and 148), the residual strength values of the samples with applied pore pressure are not significantly lower than those of the natural-humidity samples. This means that the effect of the injected fluid is not that evident as expected. This may result from the limited permeation / penetration depth.

A linear Mohr-Coulomb-approach for the residual strength of natural-humidity samples leads to:

ϕ – friction angle: 11.5°

c – cohesion: 4.4 MPa

v

ϕ – friction angle: 13.6°

c – cohesion: 3.6 MPa

of samples with pore pressure.

Further, a few samples were saturated with NaCl-brine for ca. 24 h as described in the chapters above. The aim this proceeding was to investigate the influence of fluids (like oil or brine) on the sample with its (possible) microcracks and joint inventory. Recently, the main focus was not to fully saturate the sample due to timescale reasons. A total saturation of the large-scale cylindrical samples (e.g. with pressure / vacuum) would take much longer times.

Four saturated (or wet) TC tests were performed in a confining pressure range of $1.0 \leq \sigma_3 \leq 10.0$ MPa. Therefore, a general overview about the stress-strain behaviour of such saturated v natural-humidity samples of TMS-shales can be given.

The results of the individual tests are given in the Appendices 156–159 in the form of stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1) diagrams. The data of the peak strength and strain are given in the table below (Table 4-14).

Tab. 4-14: *Strength and deformation parameters of triaxially tested saturated TMS shales. (Fracture types according to Table 3-1.)*

IfG - Lab-No.	**743/TMS117/ TC_w3_sat**	**743/TMS112/ TC_w4_sat**	**743/TMS055/ TC_w6_sat**	**743/TMS056/ TC_w7_sat**
Formation	**TMS**	**TMS**	**TMS**	**TMS**
Sample	**TMS-117**	**TMS-112**	**TMS-055**	**TMS-056**
Length l (mm)	200.253	198.508	200.630	200.513
Diameter d (mm)	99.052	99.047	100.253	99.873
Ratio l_o/d_o	2.02	2.00	2.00	2.01
Mass M (g)	3448.10	3275.10	3865.00	3566.70
Area A (cm^2)	77.058	77.050	78.938	78.340
Volume V (cm^3)	1543.10	1529.50	1583.73	1570.83
Density ρ (g/cm^3)	2.235	2.141	2.440	2.271
Temp. (°C)	23	23	23	23
σ_3 (MPa)	7.0	1.0	5.0	10.0
σ_{Dil} (MPa)	17.9	12.8	29.0	33.2
ΔV_{Dil} (%)	-0.41	-0.49	-0.41	-0.69
ε_{Dil} (%)	3.77	0.84	0.91	2.18
σ_{Fail} (MPa)	18.4	14.5	29.3	33.6
ΔV_{Fail} (%)	-0.40	-0.43	-0.41	-0.69
ε_{Fail} (%)	4.48	1.02	0.99	1.94
σ_{1Fail} (MPa)	25.41	15.55	34.29	43.58
Fracture type	B	A/D	B	B

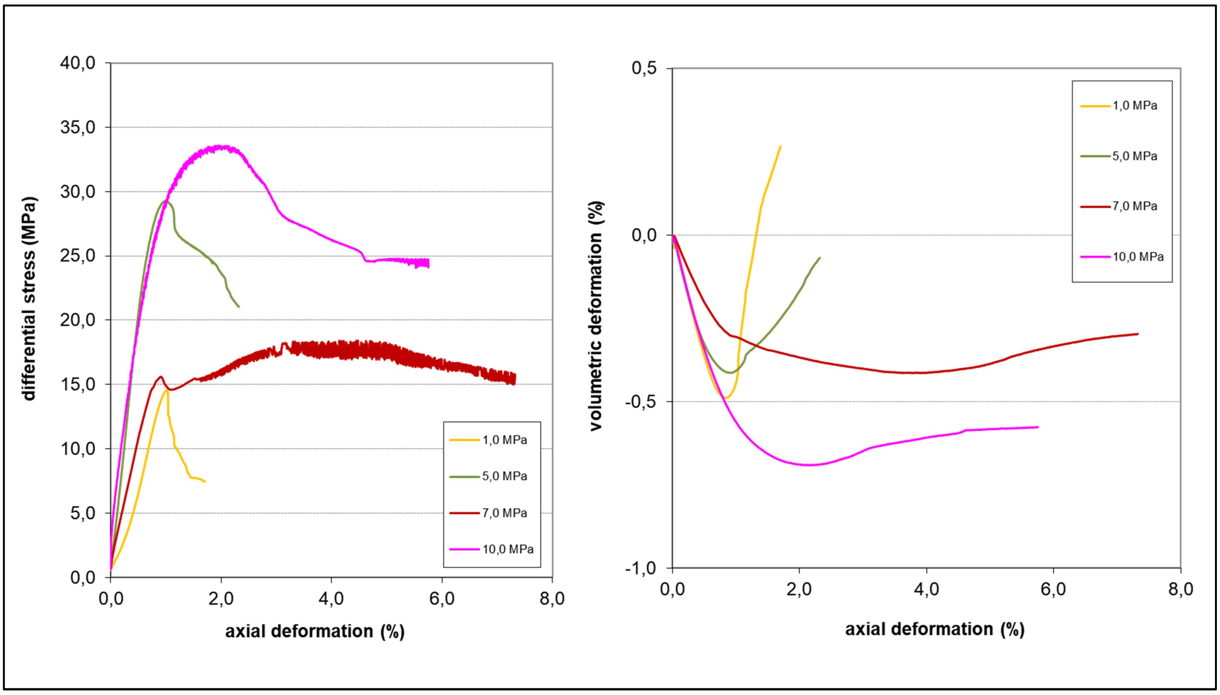


Fig. 4-12: *Left: stress-strain-diagram and Right: dilatancy-strain-diagram of the saturated shale samples from the TMS formation (short-term triaxial compression tests with confining pressures of σ_3 = 1.0 to 10.0 MPa).*

An overview of the results from the triaxial compression tests are given in Figure 4-12. Again, the curves represent the typical behaviour of strongly consolidated shales and they depict the dependency of the load bearing capacity at different confining pressures (σ_3). The curves show a scattering; the test at 7.0 MPa experiences no softening after the initial peak, but rather a second, higher peak in the "residual strength" region, which is, however, still lower than the peak strength at 5 MPa. The failure took place at defined shear planes (see Appendix 154).

The peak strength Mohr-Coulomb parameters for saturated samples are:

ϕ – friction angle: 15.8°

c – cohesion: 5.3 MPa

v

ϕ – friction angle: 19.5°

c – cohesion: 7.5 MPa

of the TMS shale samples at natural humidity, which means only a slight reduction. Considering the scatter in the peak strengths, we do not see a significant difference in strength.

Besides the triaxial test additional shear tests, along bedding planes were performed to analyse the stress and deformation behaviour during shear stress on potential weakness planes.

Therefore, 6 shale samples of the TMS formation with obvious lamination (bedding planes) were tested with direct shear test by applying constant normal load (CNL) conditions of 0.5 to 5.0 MPa. Each test was performed as two-step test with a first load-stage to determine the peak shear strength and residual strength and then a second load stage to provide the residual strength.

From the σ_n-τ-diagram the following Mohr-Coulomb-parameters could be derived (see Table 4-15):

For the maximum shear strength values:

- Cohesion c = 1.12 MPa
- Angle of friction ϕ = 41°

For the residual shear strength values:

- Angle of friction ϕ = 25°

Tab. 4-15: *Strength and Mohr-Coulomb-parameters of tested shale samples (TMS Fm.).*

Sample	Load step	shear parameter		for peak strength		for residual strength	
		σ_n	τ	c	ϕ	c	ϕ
		MPa	MPa	MPa	°	MPa	°
743/TMS/SV1	1	0.50	0.67	1.12	41	0.00	25
	1	0.50	0.34				
	2	0.75	0.39				
743/TMS/SV2	1	1.00	1.67				
	1	1.00	0.66				
	2	2.00	1.00				
743/TMS/SV3	1	3.00	5.25				
	1	3.00	1.92				
	2	4.00	2.02				
743/TMS/SV4	1	5.00	4.62				
	1	5.00	2.26				
	2	7.00	1.86				
743/TMS/SV5a	1	1.00	2.57				
	1	1.00	1.66				
	2	2.00	1.65				
743/TMS/SV5b	1	3.00	3.78				
	1	3.00	2.55				
	2	5.00	2.53				

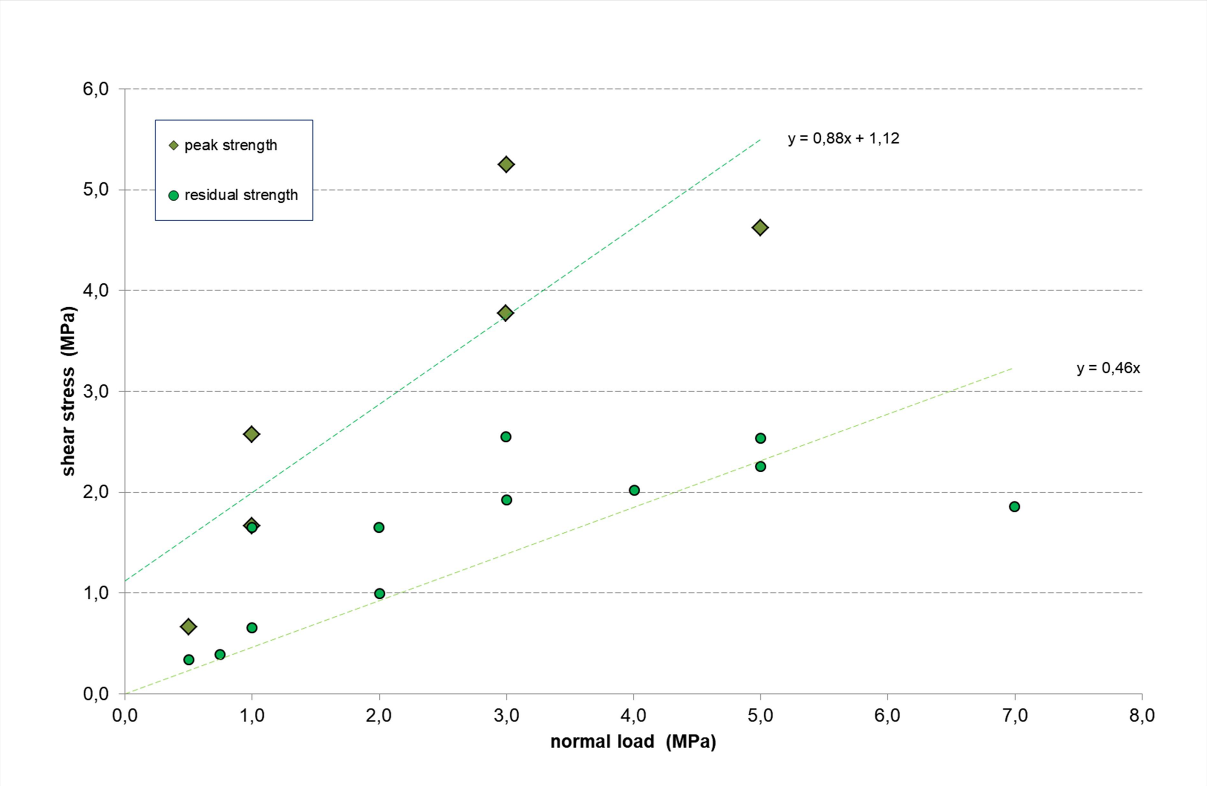


Fig. 4-13: Maximum/peak and residual shear strength values depending on the normal stress. TMS shale samples.

As to be seen in the Appendices 163-168, all shear tests are characterised by the typical behaviour of brittle rocks. After a strong and steep increase of the shear stress (at constant normal load conditions), the sample abruptly fails. This results in a strong drop of the shear stress. This is similar to the behaviour in the triaxial tests at natural humidity. After that, the shear stress remains on a constant residual strength level. This is a strong indicator that the sample completely failed and there is no further cohesion. After this first load stage a second (higher) normal load was applied to the sample, resulting in a second residual strength level. The failure pattern mostly shows obvious shear movement along a defined single bedding plane.

Another testing method of analysing potential weakness planes is the execution of direct tension tests. As stated in the methodology chapter the tension stress is applied to the sample via a bonded plate at the top (and a second one at the bottom) of the sample using a high-strength 2-component-glue.

Therefore, six samples with evident bedding planes were selected and prepared. Unfortunately, one sample failed just before testing and therefore only 5 samples were tested. Their stress-strain-diagrams are given in the Appendix 183–187. The derived direct tensile strength values were $0.04 \leq \sigma_{DTT} \leq 0.24$ MPa with a mean value of 0.10 MPa which is very low. This indicates that the bedding planes are weakness planes.

By splitting tests (“Brazilian” tests), the tensile strength can be indirectly determined. But, it has to be taken into account, that the bedding planes and any other orientation influence the value of the tensile strength due to anisotropy effects. Here, the orientation was nearly perpendicular to the bedding and high tensile strength values were expected (Figure 4-14).

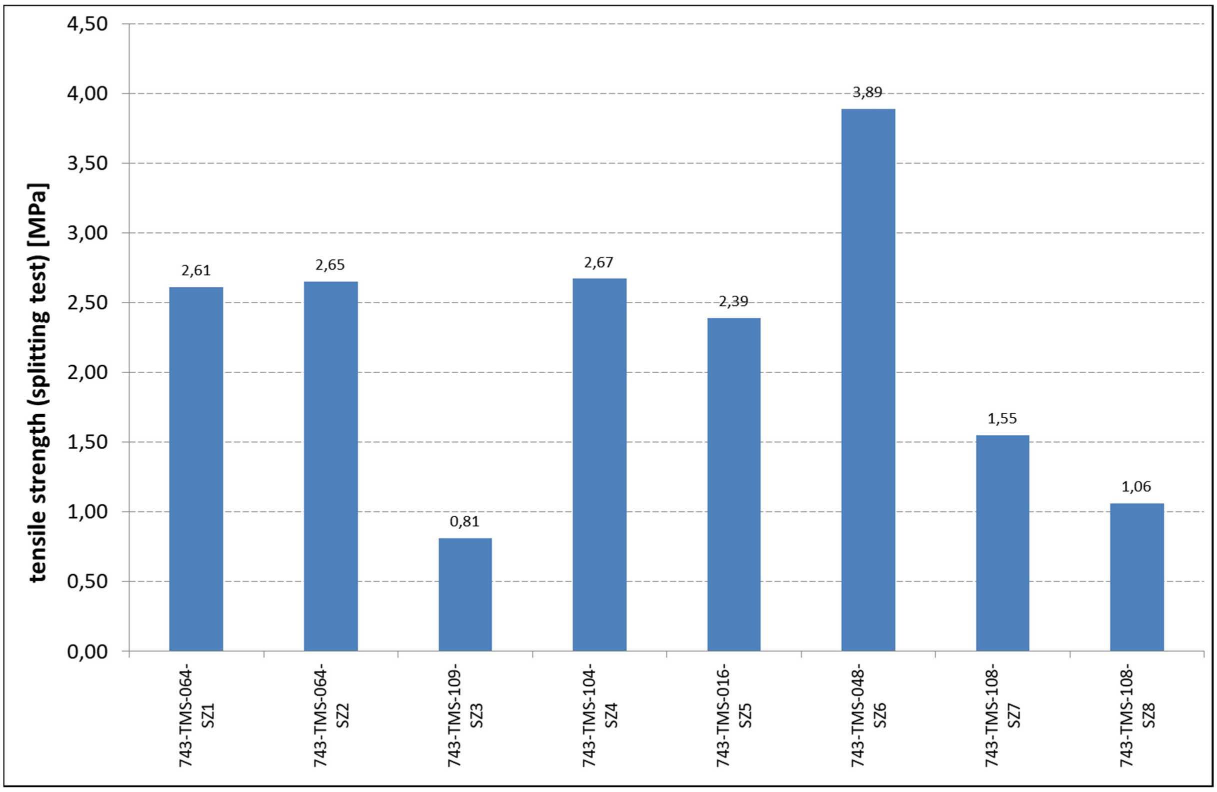


Fig. 4-14: *Maximum tensile strength values of shale samples of the Tabuleiro Fm.*

A photo-documentation of the testing and the failure development is given in Appendices 169 and 170. The single test diagrams are documented in Appendices 172–179.

4.12 PRP – Pure Rock Salt

Besides the typical overburden rocks like limestones, sandstones, argillites etc., other occurring rocks are of major interest, especially the salt rocks of the PRP formation. Those are represented by relatively pure rock salt as well as by rock salt with evident impurities. The depth range of extracted saliferous rock core material was from 914 m down to 1092 m; note that the Paripuera formation contains numerous shale layers of thickness up to several metres; those are tested separately and presented in Section 4.14.

The pure halite is characterised by its fine grain sizes. Although it is termed as pure halite, some obvious layering and predominant orientations were evident, especially in the creep test samples (see Appendices 190–193 and 205–210). Further, it has to be mentioned that the observed bulk densities of the creep test samples (and also TC samples) was ≤ 2.14 g/cm³ which is lower than expected.

Seven triaxial strength tests were performed. Ultrasonic measurements were successful in a few cases and led to the following dynamic elastic constants:

E_d (GPa) = 32,77
K_d (GPa) = 20,50
G_d (GPa) = 13,28
ν_d (-) = 0,234

which seems to be reasonable for rock salt.

The TC tests were carried out in the confining pressure range $0.2 \le \sigma_3 \le 5.0$ MPa at 57°C (accordant to in-situ temperature conditions), but, two of them also at other temperature conditions (23°C ad 90°C; for comparison reasons).

The test results are given in the Appendices 197–203 in the form of a stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1). The data of the peak strengths strains are given in the table below (Table 4-16).

Tab. 4-16a: *Strength and deformation parameters of triaxially tested pure halite samples (PRP) samples.*

IfG - Lab-No.	**743/HAL/YGM 004/TC_d1**	**743/HAL/YGM 008/TC_d2**	**743/HAL/YGM 007/TC3**	**743/HAL/YGM 009/TC4**
Formation	**PRP**	**PRP**	**PRP**	**PRP**
Sample	**YGM_004**	**YGM008**	**YGM007**	**YGM009**
Length l (mm)	192.445	192.415	192.315	192.493
Diameter d (mm)	96.440	96.375	96.535	96.448
Ratio l_o/d_o	2.00	2.00	1.99	2.00
Mass M (g)	3018.50	3019.6	3016.3	3009.9
Area A (cm²)	73.047	72.949	73.191	73.059
Volume V (cm³)	1405.76	1403.65	1407.58	1406.34
Density ρ (g/cm^3)	2.147	2.151	2.143	2.140
$V_{p\text{-axial}}$ (km/s)	4.22	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	4.48	-	4.43	4.21
$V_{p\text{-radial: b-d}}$ (km/s)	4.37	4.42	4.41	-
$V_{s\text{-axial}}$ (km/s)	2.49	-	-	-
E_d (GPa)	32.77	-	-	-
K_d (GPa)	20.50	-	-	-

G_d (GPa)	13.28	-	-	-
v_d	0.234	-	-	-
Temp. (°C)	23	57	57	57
σ_3 (MPa)	1.0	1.0	0.2	0.5
σ_{Dil} (MPa)	9.8	7.3	4.6	6.2
ΔV_{Dil} (%)	-0.03	-0.03	-0.02	-0.03
ε_{Dil} (%)	0.08	0.09	0.06	0.08
σ_{Fail} (MPa)	32.2	28.7	20.9	23.9
ΔV_{Fail} (%)	3.04	2.02	1.63	1.69
ε_{Fail} (%)	6.06	9.86	4.20	5.68
σ_{1Fail} (MPa)	33.17	29.68	21.13	24.38
Fracture type	B	B	B	B

Tab. 4-16b: *Strength and deformation parameters of triaxially tested pure halite samples (PRP) samples (continued).*

IfG - Lab-No.	743/HAL/YGM004/TC_d1	743/HAL/YGM008/TC_d2	743/HAL/YGM007/TC3
Formation	**PRP**	**PRP**	**PRP**
Sample	**YGM_004**	**YGM008**	**YGM007**
Length l (mm)	192.445	192.415	192.315
Diameter d (mm)	96.440	96.375	96.535
Ratio l_o/d_o	2.00	2.00	1.99
Mass M (g)	3018.50	3019.6	3016.3
Area A (cm^2)	73.047	72.949	73.191
Volume V (cm^3)	1405.76	1403.65	1407.58
Density ρ (g/cm^3)	2.147	2.151	2.143
$V_{p\text{-axial}}$ (km/s)	4.22	-	-
$V_{p\text{-radial: a-c}}$ (km/s)	4.48	-	4.43
$V_{p\text{-radial: b-d}}$ (km/s)	4.37	4.42	4.41
$V_{s\text{-axial}}$ (km/s)	2.49	-	-
E_d (GPa)	32.77	-	-
K_d (GPa)	20.50	-	-
G_d (GPa)	13.28	-	-
v_d	0.234	-	-
Temp. (°C)	23	57	57
σ_3 (MPa)	1.0	1.0	0.2
σ_{Dil} (MPa)	9.8	7.3	4.6
ΔV_{Dil} (%)	-0.03	-0.03	-0.02
ε_{Dil} (%)	0.08	0.09	0.06

σ_{Fail} (MPa)	32.2	28.7	20.9
ΔV_{Fail} (%)	3.04	2.02	1.63
ε_{Fail} (%)	6.06	9.86	4.20
σ_{1Fail} (MPa)	33.17	29.68	21.13
Fracture type	D	D	D

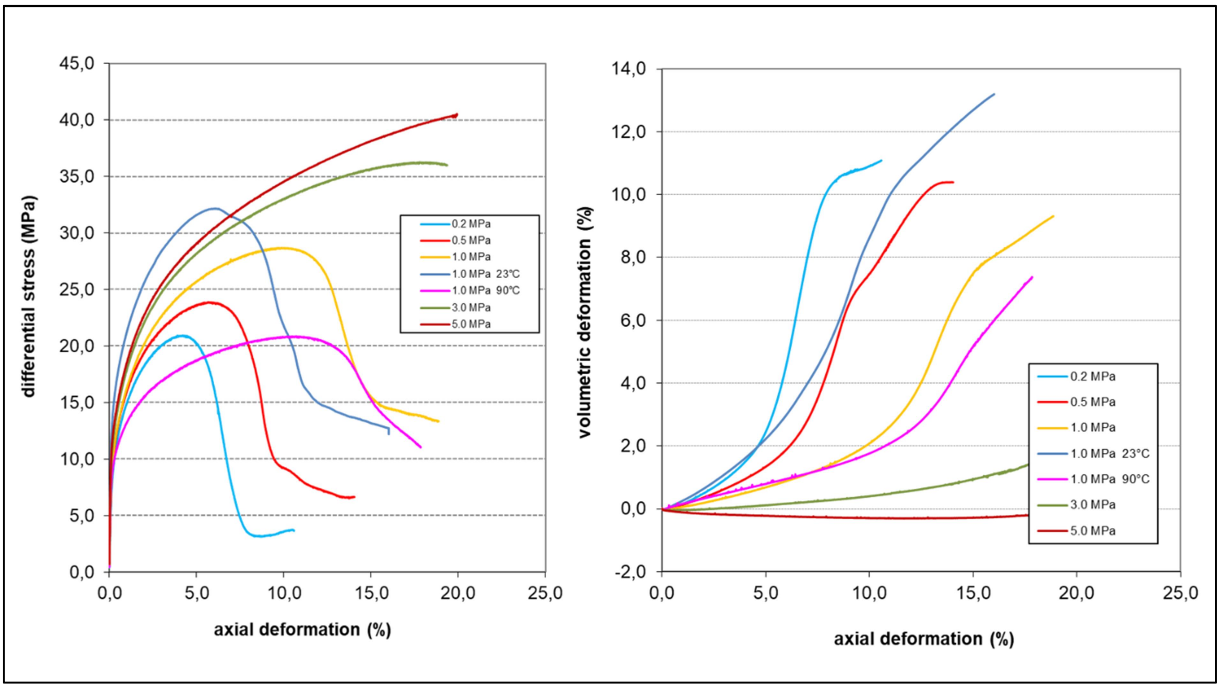


Fig. 4-15: *__Left:__ stress-strain-diagram and __Right:__ dilatancy-strain-diagram of the pure halite samples from the PRP formation (short-term triaxial compression tests with confining pressures of σ_3 = 0.2…5.0 MPa).*

Summarised results from the triaxial compression tests are represented in Figure 4-15. Here, the curves depict typical stress-strain behaviour as known of rock salt. Further, a dependency (peak strength and strain at failure) of the temperature is evident (as known from previous investigations).

Here, a linear Mohr-Coulomb-approach will not represent and fit well the strength boundary of the rock salt, where the failure strength boundary (Figure 4-16) is obviously strongly non-linear, which has to be considered by selecting an appropriate failure criterion.
Due to the ductile deformation behaviour, a determination of the static elastic parameters at 50% of the peak strength was not considered reasonable for the rock salt samples.

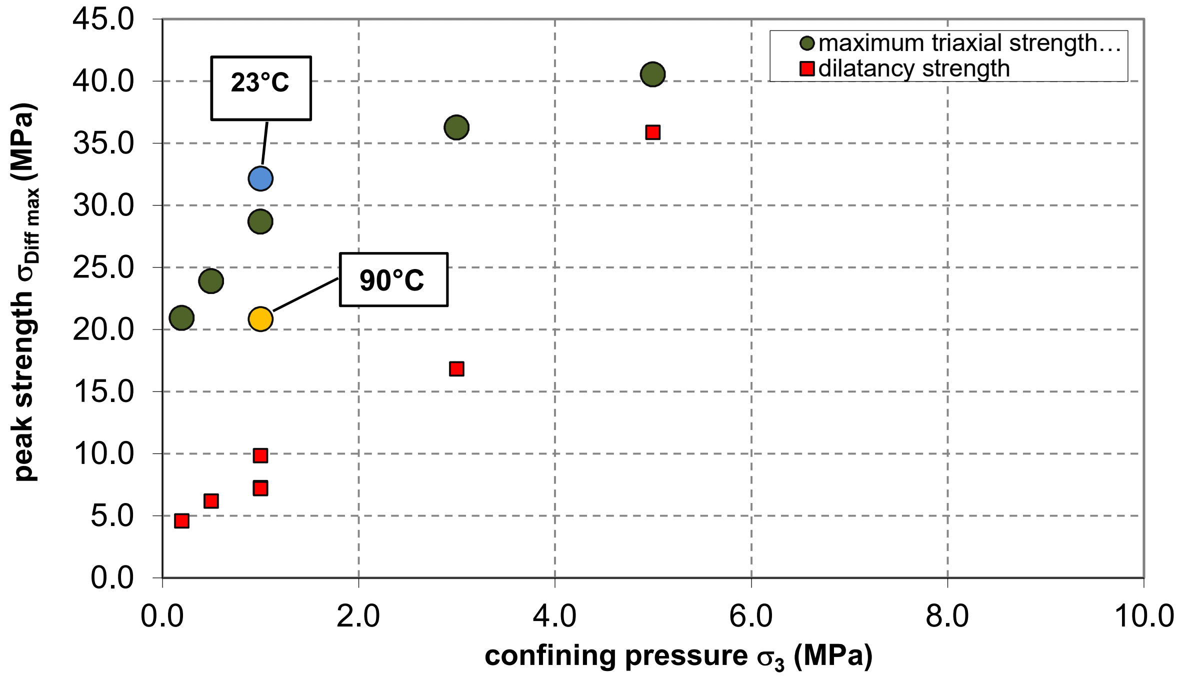


***Fig. 4-16**: Maximum principal stress v minimum principal stress: strength parameters of rock salt from the Paripuera formation.*

For the long-term, creep tests, twelve samples (eight of pure and four of the more impure rock salt) were prepared from the rock salt. Their dimensions were 40 mm in diameter and 80 mm in length. As stated above, their densities were a little bit lower than expected: ρ_{pure} = 2.12 g/cm³ and ρ_{impure} = 2.14 g/cm³.

As mentioned above, all samples were installed into heatable triaxial cells. The test temperature inside was 53°C. For comparison and data evaluation reasons one sample was tested at room temperature and one at 80°C. After a hydrostatic consolidation for about 14 days, a constant axial stress was applied, resulting in deviatoric stress conditions. Each test was held constant (axial load) for 50-60 days until quasi-stationary creep (or until reaching a technical limit for the axial strain. Then the axial load was decreased resulting in slightly lower deviatoric stress conditions. Then, the second load step was held constant, again, until quasi-stationary creep.

The creep test conditions and results (i.e. referred to the stationary creep rates ε_{cs}, as determined by a linear fit of the quasi-stationary part of the creep curve) of these samples are summarised in Table 4-17. The photo documentation of the creep test samples is given in the Appendices 205–210, as well as the single creep test curves given as creep deformation v time/duration diagrams (Appendices 213–224).

Tab. 4-17: *Long-term creep tests of salt rocks from PRP unit – loading conditions and quasi-stationary creep rates. In the last column, values in parentheses indicate current values in test that are still running. The test TCC10 had to be stopped in the isotropic phase due to a technical problem.*

sample	material	differential stress $\Delta\sigma$ (MPa)	temperature (°C)	creep rate (1/d)
743/cx1029/TCC1	pure halite	12	53	2.2E-04
743/cx1029/TCC1	pure halite	10	53	(5.4E-05)
743/cx1029/TCC2	pure halite	12	53	4.7-04
743/cx1029/TCC2	pure halite	10	53	(1.0E-04)
743/cx1029/TCC3	pure halite	16	53	8.8E-04
743/cx1029/TCC3	pure halite	14	53	(4.7E-04)
743/cx1029/TCC4	pure halite	19	53	2.2E-03
743/cx1029/TCC4	pure halite	16	53	3.5E-04
743/cx1030/TCC5	pure halite	22	53	7.9E-03
743/cx1030/TCC5	pure halite	19	53	(strain limit reached)
743/cx1030/TCC6	pure halite	25	53	4.9E-03
743/cx1030/TCC6	pure halite	10	53	(strain limit reached)
743/cx1030/TCC7	pure halite	16	26	3.0E-04
743/cx1030/TCC7	pure halite	14	26	(7.9E-05)
743/cx1030/TCC8	pure halite	16	80	4.5E-04
743/cx1030/TCC8	pure halite	14	80	(2.0E-05)
743/cx1102/TCC9	dirty salt; impure	16	53	7.3E-04
743/cx1102/TCC9	dirty salt; impure	14	53	(2.0E-04)
743/cx1102/TCC11	dirty salt; impure	18	53	2.2E-03
743/cx1102/TCC11	dirty salt; impure	16	53	(strain limit reached)
743/cx1102/TCC12	dirty salt; impure	24	53	9.4E-03
743/cx1102/TCC12	dirty salt; impure	22	53	(strain limit reached)
743/cx1102/TCC13	dirty salt; impure	8	53	1.29E-04
743/cx1102/TCC13	dirty salt; impure	10	53	(2.1E-04)

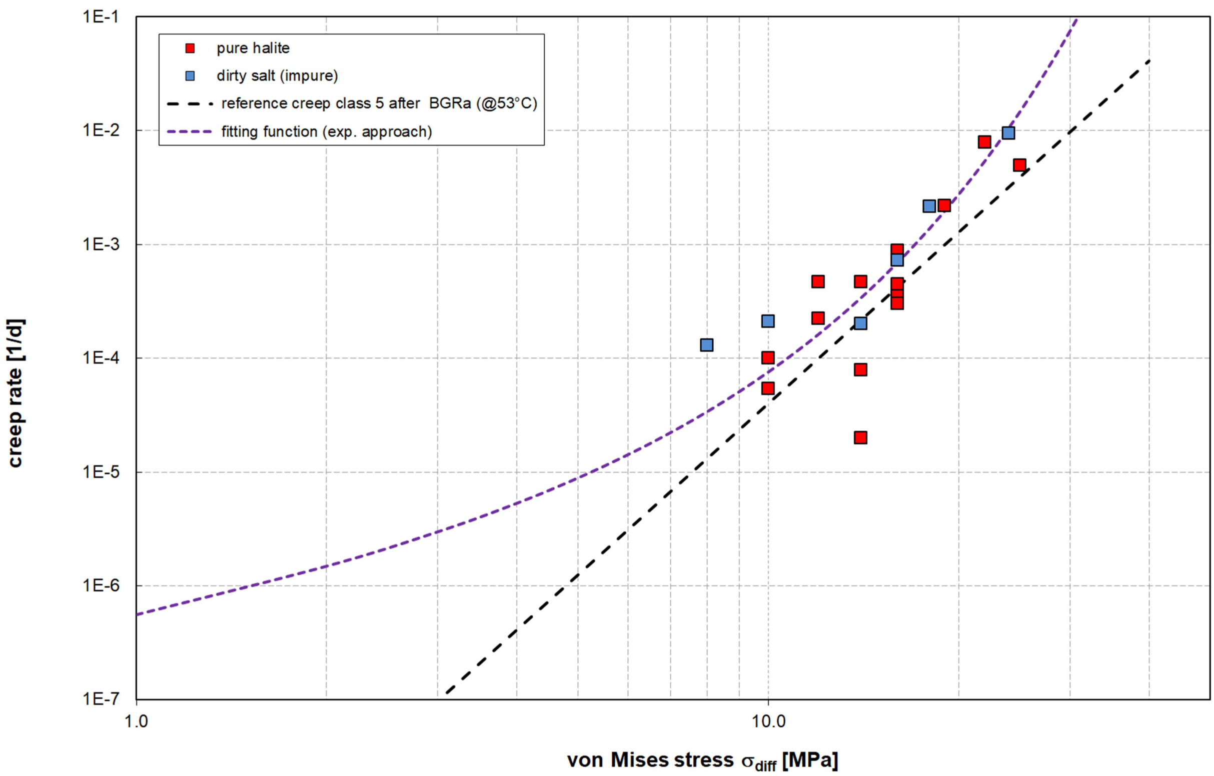


Fig. 4-17: *Creep rate dependence of pure and impure salt rocks of PRP Fm. The non-linear fits represent the exponential creep approach. The stippled line depicts the typical rock salt creep behaviour (at 53°C) referring to a reference creep class (BGRa, straight line) and an exponential fit.*

The results of both varieties of occurring salt units of PRP are shown in creep rate v differential stress plot in Figure 4-17.

The plot indicates that the new data (of both varieties of rock salt) do more or less correspond to the so-called reference creep class 5 of the BGRa creep law[7], which describes a typical creep behaviour of rock salt. In other words, means the present samples represent a moderately creeping rock salt.

As came out by new scientific investigations, especially by lab tests in the low stress regime ($\Delta\sigma$ < 10 MPa) a creep mechanism change occurs in this stress region resulting in higher creep rates. Therefore, it is generally recommended to describe the relation between stress and creep rate for the salt rocks by a quasi-non-linear creep parameter fit / approach (in the log/log-diagram). This represents the creep mechanism change in a low and high deviatoric stress area. The parameters m and η_0^M could be estimated from a logarithmic plot of Maxwell viscosity η^M v differential stress $\Delta\sigma$. An exponential approach is described with

$$\dot{\varepsilon_M} \frac{\sigma_{eff}}{3 \cdot \eta_M} \cdot e^{(m \cdot \sigma_{eff})}$$

with $\eta_M = 8*10^5$ and m = 0.29 (valid for both types of rock salt).

4.13 PRP – Impure Rock Salt

The long-term tests (creep tests, TCC) were performed on the impure rock salt samples. Their results are presented together with the pure halites in the previous section.

4.14 SHL – Shale from Paripuera Formation

In the depth of 1007 to 1020 m some massive shale layers occurred as intercalations between the dominating salt rocks. There, of few core meters could be extracted and used for laboratory investigations. Unfortunately, the contact planes between salt and shale were not intact and couldn’t be tested. Nevertheless, a suitable amount of core segments representing massive shale was available and test specimens could be prepared, especially for triaxial tests and direct shear tests.

[7] See e.g. Hunsche U, Hampel A. (1999): Rock salt – the mechanical properties of the host rock material for a radioactive waste repository. Eng Geol 1999;52(3e4):271e91. https://doi.org/10.1016/S0013-7952(99)00011-3

The slaty core material from this unit was quite compact but an obvious thin lamination with 45° dipping bedding planes was observed. The mean bulk density of the TC-test samples is 1.93 g/cm³. Ultrasonic measurements were – due to the strong bedding – not possible.

Comparable to the investigations of all other overburden rocks, the TC test were carried out again in the confining pressure range $0.5 \leq \sigma_3 \leq 10.0$ MPa.

The results of the individual triaxial tests are given in the Appendices 232–236 in form of stress – strain (axial stress σ_1 respectively confining pressure p_c v strain ε_1) diagrams. The data of the peak strength strain values are given in the table below (Table 4-18).

Tab. 4-18: *Strength and deformation parameters of triaxially tested shale samples from the Paripuera formation (SHL) samples.*

IfG - Lab-No.	**743/SHL003/TC_d1**	**743/SHL004/TC_d2**	**743/SHL005/TC_d3**	**743/SHL001/TC_d4**	**743/SHL001/TC_d5**
Formation	**SHL**	**SHL**	**SHL**	**SHL**	**SHL**
Sample	**SHL_003**	**SHL_004**	**SHL_005**	**SHL_001**	**SHL_001**
Length l (mm)	198.105	197.508	200.715	197.745	199.798
Diameter d (mm)	99.798	100.747	99.785	100.507	100.400
Ratio l_o/d_o	1.99	1.96	2.01	1.97	1.99
Mass M (g)	3036.80	3046.5	2951.5	3091.2	3003.3
Area A (cm²)	78.223	79.718	78.202	79.338	79.169
Volume V (cm³)	1549.63	1574.49	1569.64	1568.87	1581.79
Density ρ (g/cm³)	1.960	1.935	1.880	1.970	1.899
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 (MPa)	0.5	1.0	3.0	5.0	10.0
σ_{Dil} (MPa)	9.7	10.3	6.6	12.1	13.0
ΔV_{Dil} (%)	-0.48	-0.69	-1.82	-1.67	-1.55
ε_{Dil} (%)	0.96	1.24	10.94	10.88	9.19
σ_{Fail} (MPa)	9.8	10.3	8.4	12.2	15.8
ΔV_{Fail} (%)	-0.48	-0.69	-1.61	-1.68	-1.44
ε_{Fail} (%)	0.99	1.23	5.45	11.02	3.78
σ_{1Fail} (MPa)	10.27	11.28	11.39	17.23	25.81
Fracture type	B*	B*	B*/B	B*	B*
E_{50} (GPa)	1.28	1.20	1.10	0.49	2.15
ν_{50}	0.21	0.20	0.38	0.43	0.43
K_{50} (GPa)	0.73	0.68	1.58	1.23	4.92
G_{50} (GPa)	0.53	0.50	0.40	0.17	0.75

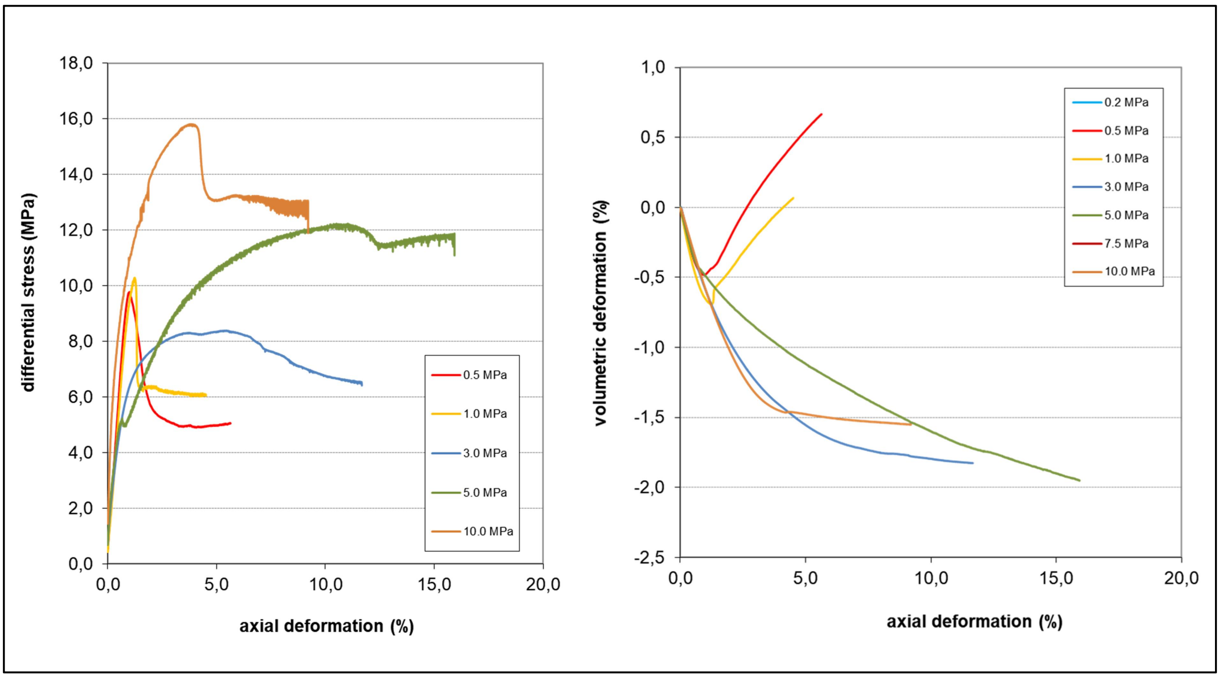


Fig. 4-18: *<u>Left:</u> stress-strain-diagram and <u>Right:</u> dilatancy-strain-diagram of shale samples from the Paripuera formations (unit SHL; short-term triaxial compression tests with confining pressures of σ_3 = 0.5 to 10.0 MPa).*

Summarised results from the triaxial compression tests are given in Figure 4-18. The curves depict the dependency of the load bearing capacity at different confining pressures (σ_3). The samples show evident brittle behaviour in their failure development and test progress. As to be seen in the photo-documentation (Appendix 227), all samples failed along shear planes which are parallel to the bedding planes. On these shear planes slickensides occurred.

A linear Mohr-Coulomb-approach (based on the five triaxial test results (for σ_3 = 0.5 to 10 MPa)) results in:

ϕ – friction angle: 14.4°

c – cohesion: 3.4 MPa

The dynamic elastic parameters were determined with:

E – Young's modulus: 3.1 (GPa)

ν – Poisson's ratio: 0.20

The static elastic parameters (Appendix 231) are similar to the TMS samples in that the stiffness depends only weakly on the confining stress while Poisson's ratio changes form about 0.2 to more than 0.4 for higher σ_3.

Besides the triaxial test further shear tests along the bedding planes were performed to investigate the stress and deformation behaviour during shear stress on potential weakness planes.

Therefore, 3 shale samples with obvious lamination (bedding planes) were tested with direct shear test by applying constant normal load (CNL) conditions of 0.5 to 4.0 MPa. Each test was performed as two-step test with a first load-stage to determine the peak shear strength and residual strength and then a second load stage to provide the residual strength.

From the σ_n-τ-diagram the following Mohr-Coulomb-parameters could be derived (see Table 4-19 and Figure 4-19):

For the maximum shear strength values:

- Cohesion c = 0.48 MPa
- Angle of friction ϕ = 38°

For the residual shear strength values:

- Angle of friction ϕ = 21°

Tab. 4-19: *Strength and Mohr-Coulomb-parameters of tested shale samples (PRP unit).*

			Strength values		Mohr-Coulomb		
		Load step	σ_n	τ	c	ϕ max	ϕ res
			MPa	MPa	MPa	°	°
743/SHL/SV1	shale	1	0.50	0.91	0.48	38	21
		1	0.50	0.38			
		2	1.00	0.55			
743/SHL/SV2	shale	1	0.75	1.01			
		1	0.75	0.56			
		2	1.50	0.68			
743/SHL/SV3	shale	1	2.00	2.04			
		1	2.00	1.01			
		2	4.00	1.31			

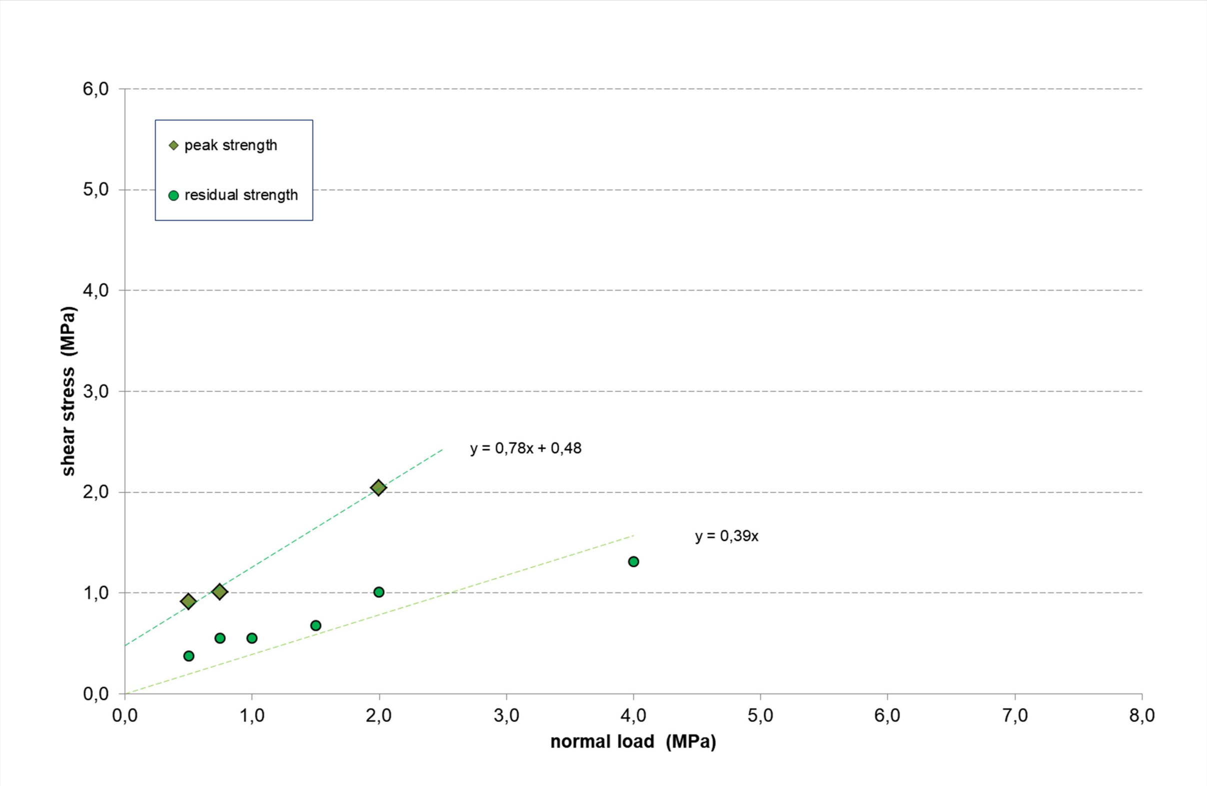


Fig. 4-19: *Maximum/peak and residual shear strength values depending on the normal stress. Shale samples (of PRP Fm.).*

As to be seen in Appendices 228–230, all shear tests are characterised by the typical behaviour of brittle rocks. After a strong and steep increase of the shear stress (at constant normal load conditions), the sample abruptly fails. This results in a strong drop of the shear stress. This is similar to the behaviour in the triaxial tests. After that, the shear stress remains on a constant residual strength level. This is a strong indicator that the sample completely failed and there is no further cohesion. After this first load stage a second (higher) normal load was applied to the sample, resulting in a second residual strength level. The failure pattern shows obvious shear movement along no single but multiple bedding planes.

5 SUMMARY

The Institut für Gebirgsmechanik GmbH (IfG) was commissioned by Braskem with an extensive laboratory programme to characterise the salt and overburden formations in the Maceió cavern field. The programme comprises triaxial compression tests (at natural humidity, with pore pressure or partial saturation), tensile tests (direct and Brazilian), long-term creep test on salt, and direct shear tests. Braskem has provided approximately 130 m of drill core from the stratigraphic well PE04, drilled in 2020. The material includes rock salt and shale interbedding from the Paripuera formation (the leaching horizon) as well as sedimentary overburden rocks (shales, sandstones, conglomerates, limestones); 13 lithological units have been identified based on stratigraphy and lithology within strata.

The following amount of tests has been performed and analysed (see Section 3 for a description of the test types):

- 67 triaxial tests at natural humidity (TC_nat)
- 8 triaxial tests with fluid influence (saturated samples or applied pore pressure, TC_wet)
- 6 direct tensile tests (DTT)
- 8 splitting tensile tests (“Brazilian tests”, STT)
- 13 direct shear tests (DST)
- 12 triaxial creep tests (TCC)

The samples were characterised petrophysically (density, ultrasonic wave velocities and dynamic elastic parameters (if possible), photographic documentation).

The test results form the basis to derive parameters for the parallel numerical modelling of the cavern field.

In Section 4 and the Appendix, we present all available tests. The main results of the overburden strata are summarised in Table 5-1.

Tab. 5-1: *Main rock-mechanical parameters of the strata in Maceió, as determined from the available tests. (Symbols in the second row denote density, Young’s modulus, Poisson’s ratio, cohesion, friction angle, direct and splitting tensile strength, cohesion and friction angle (from shear tests).) Note that the elastic constants for rock salt are determined from ultrasonic wave velocities. Mohr-Coulomb parameters for the PCGL unit refer to matrix samples.*

		TC_nat				Tensile		Shear	
	ρ	E	ν	C	ϕ	σ_{dtt}	σ_{brazil}	c	φ
	g/cm^3	GPa	1	MPa	°	MPa	MPa	MPa	°
MAR	2.16			0.7	27.9				
MAG	1.99			0.8	24.2				
MOS	2.2			2.2	33.2				
MRT	2.15			1.4	25.3				
IBU	2.21	16.5	0.06	9.8	6.5				

PAR		6.4	0.21	2.4	22.5				
PCGL		8.2	0.31	2.9	22.4				
PI				2.0	28.3				
PF		8.9	0.14	4.5	13.0				
TMS	2.3	6.5	0.14	7.5	19.5	0.10	2.20	1.12	41
PRP (Rock salt)	2.14	32.7	0.23						
PRP(Shale)	1.93	3.1	0.20	3.4	14.4			0.48	38

The stationary creep behaviour of the rock salt, which is the major influence for the subsidence over a stable cavern field, is shown in Figure 5-1.

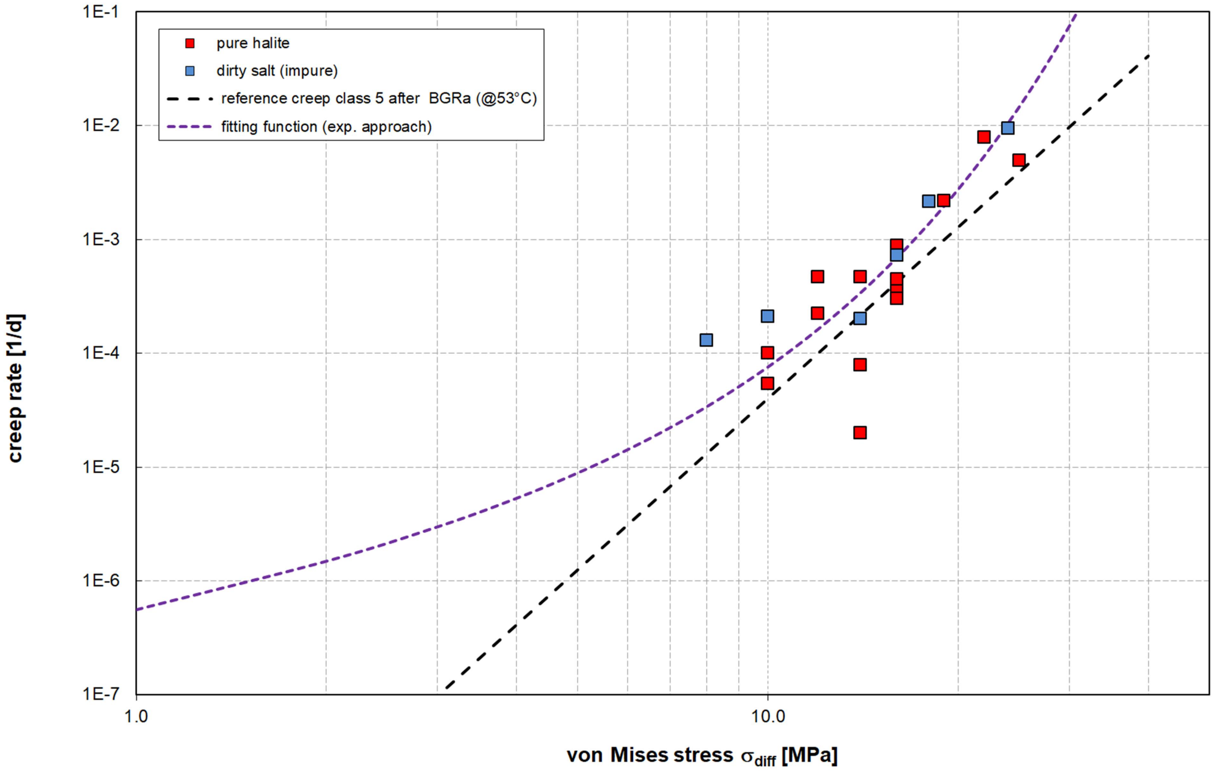


Fig. 5-1: *Creep rate dependence of pure and impure salt rocks of PRP Fm. The non-linear fits represent the exponential creep approach. The stippled line depicts the typical rock salt creep behaviour (at 53°C) referring to a reference creep class (BGRa, straight line) and an exponential fit. (Repeated from Figure 4-17.)*

INSTITUT FÜR GEBIRGSMECHANIK GMBH

overview of delivered core boxes with core segments of various stratigraphical units and rock suites

Appendix 1

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

INSTITUT FÜR GEBIRGSMECHANIK GMBH

**example of drilled cores (here TMS unit)
and available core segments at IfG Leipzig (framed in red)**

Appendix 2

***B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"***

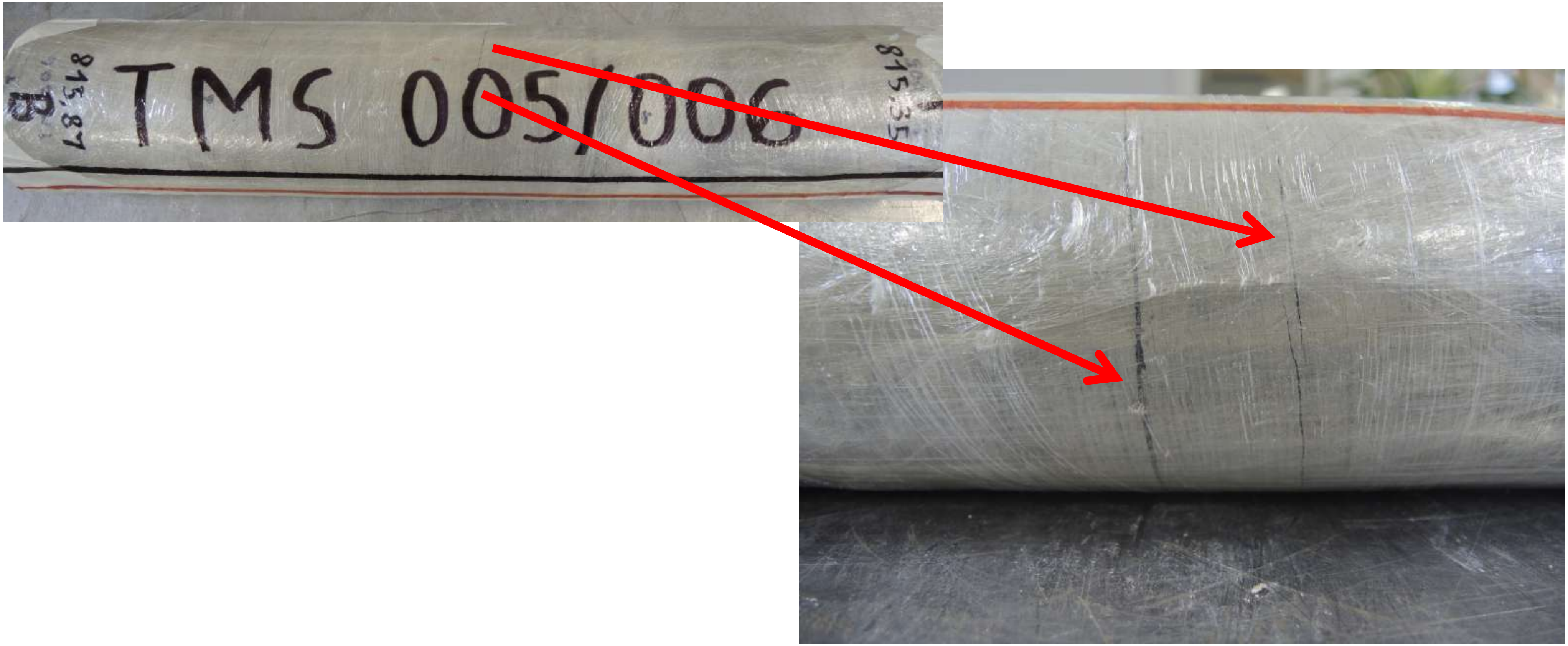
TMS-026/027
(892)

IfG INSTITUT FÜR GEBIRGSMECHANIK GMBH

example of available core segments with a pre-selection (for preparation and planned testing)

Appendix 3

B IfG 22/2021
“Rock Mechanical Investigations –
Maceio – BRASKEM”



INSTITUT FÜR GEBIRGSMECHANIK GMBH

photo documentation of BRASKEM (after drilling) and core conditions AFTER delivery → open cracks

Appendix 4

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	**9**	**9**		**6**	**6**		
MAG (Marituba Argilito)	**9**	**9**		**6**	**6**		
MO (Mosqueiro)	**9**	**9**		**6**	**6**		
MRT (Marituba II)	**4**						
IBU (Ibura)	**9**	**9**		**6**	**6**		
PAR (Poção Arenito)	**9**	**9**		**6**	**6**	**3**	
PCG (Poção Conglomerado)	**9**	**9**		**6**	**6**	**3**	
PI (Poção Intercalado)	**9**	**9**		**6**	**6**	**3**	
PF (Poção Folhelho)	**9**	**9**		**6**	**6**	**3**	
TMS (Tabuleiro)	**9**	**9**	**5**	**6**	**6**	**6**	
PRP Pure Halite	**7**						**8**
PRP Intercalated Halite	**8**		**5**		**6**	**6**	**4**
PRP Shale from Halite	**6**		**5**		**6**		

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	**9**	**9**		**6**	**6**		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/MAR003/TC_d1	743/MAR030/TC_d2	743/MAR028/TC_d3	743/MAR029/TC_d4	743/MAR029/TC_d5
Rock Type / Unit	MAR	MAR	MAR	MAR	MAR
Sample	MAR_003	MAR_030	MAR_028	MAR_029	MAR_029
Depth (m)					
Length l (mm) =	192.608	178.480	183.718	190.180	176.373
Diameter d (mm) =	97.512	97.768	96.433	98.027	98.303
Ratio l_o/d_o =	1.98	1.83	1.91	1.94	1.79
Mass M (g) =	2859.30	2900.1	2894.1	3109.0	2871.2
Area A (cm^2) =	74.680	75.073	73.037	75.471	75.897
Volume V (cm^3) =	1438.40	1339.90	1341.82	1435.31	1338.61
Density ρ (g/cm^3) =	1.988	2.164	2.157	2.166	2.145
US L (h) – p	-	-	-	-	-
US Q1 (a/c) – p	-	-	-	-	-
US Q2 (b/d) – p	-	-	-	-	-
US L (h) – s	-	-	-	-	-
US L (h) - p(s)	-	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-
E_d (GPa) =	-	-	-	-	-
K_d (GPa) =	-	-	-	-	-
G_d (GPa) =	-	-	-	-	-
ν_d =	-	-	-	-	-
	TC	**TC**	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.2	0.5	1.0	3.0	5.0
σ_{Dil} (MPa) =	2.3	2.3	3.4	7.2	10.1
ΔV_{Dil} (%) =	-0.27	-0.29	-0.47	-0.74	-1.12
ε_{Dil} (%) =	0.44	0.68	1.09	2.15	4.24
σ_{Fail} (MPa) =	3.0	2.9	4.0	8.0	11.0
ΔV_{Fail} (%) =	-0.14	0.19	-0.32	-0.50	-0.63
ε_{Fail} (%) =	0.71	2.04	1.95	4.08	10.92
σ_{1Fail} (MPa) =	3.18	3.39	5.04	11.04	15.99
α (°) =	65	65	65	65	65
σ_n (MPa) =	0.73	1.02	1.72	4.44	6.96
τ (MPa) =	1.14	1.11	1.55	3.08	4.21
ϕ=	**27.9**				
C=	**0.7**				

BEFORE:

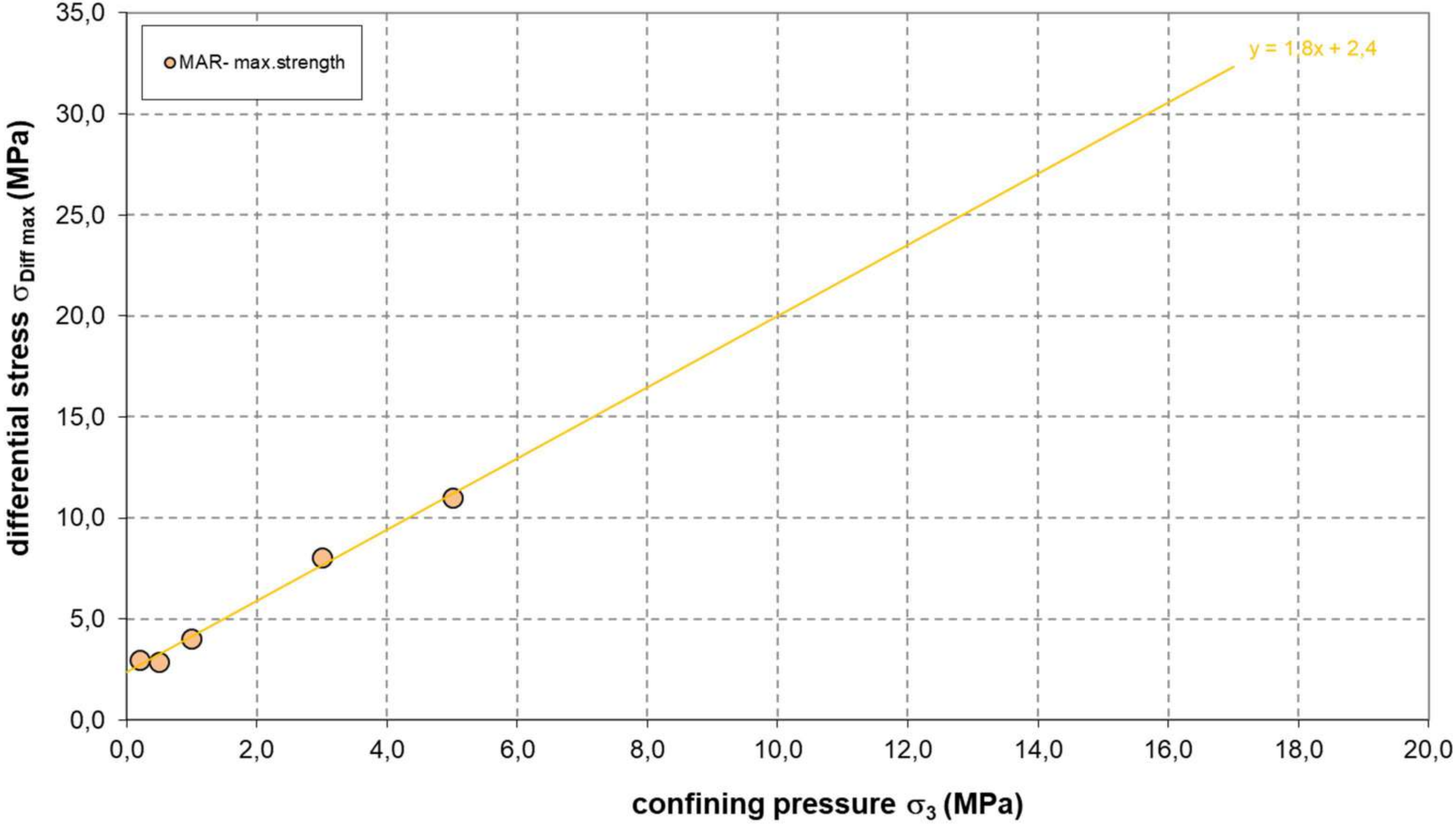
AFTER:

σ_3 = 0.2 MPa | σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 3.0 MPa | σ_3 = 5.0 MPa

Samples for triaxial strength tests (TC_nat)

Unit – MAR (Marituba Arenito)

→ photo-documentation before and after the test



INSTITUT FÜR GEBIRGSMECHANIK GMBH

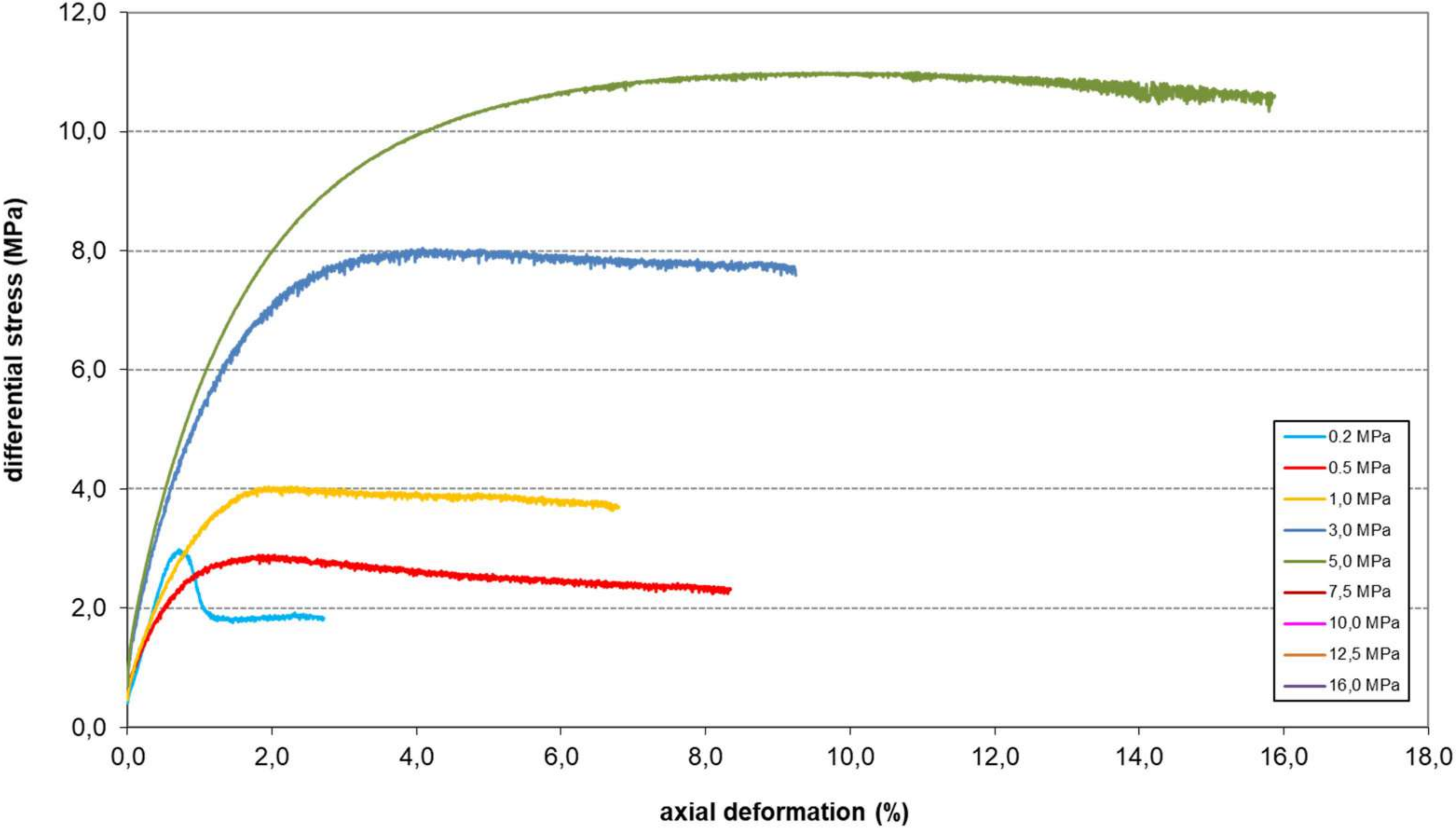
Triaxial strength tests (TC_nat)

Unit – MAR (Marituba Arenito)

→ maximum strength values dependent on the radial stress

Appendix 9

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

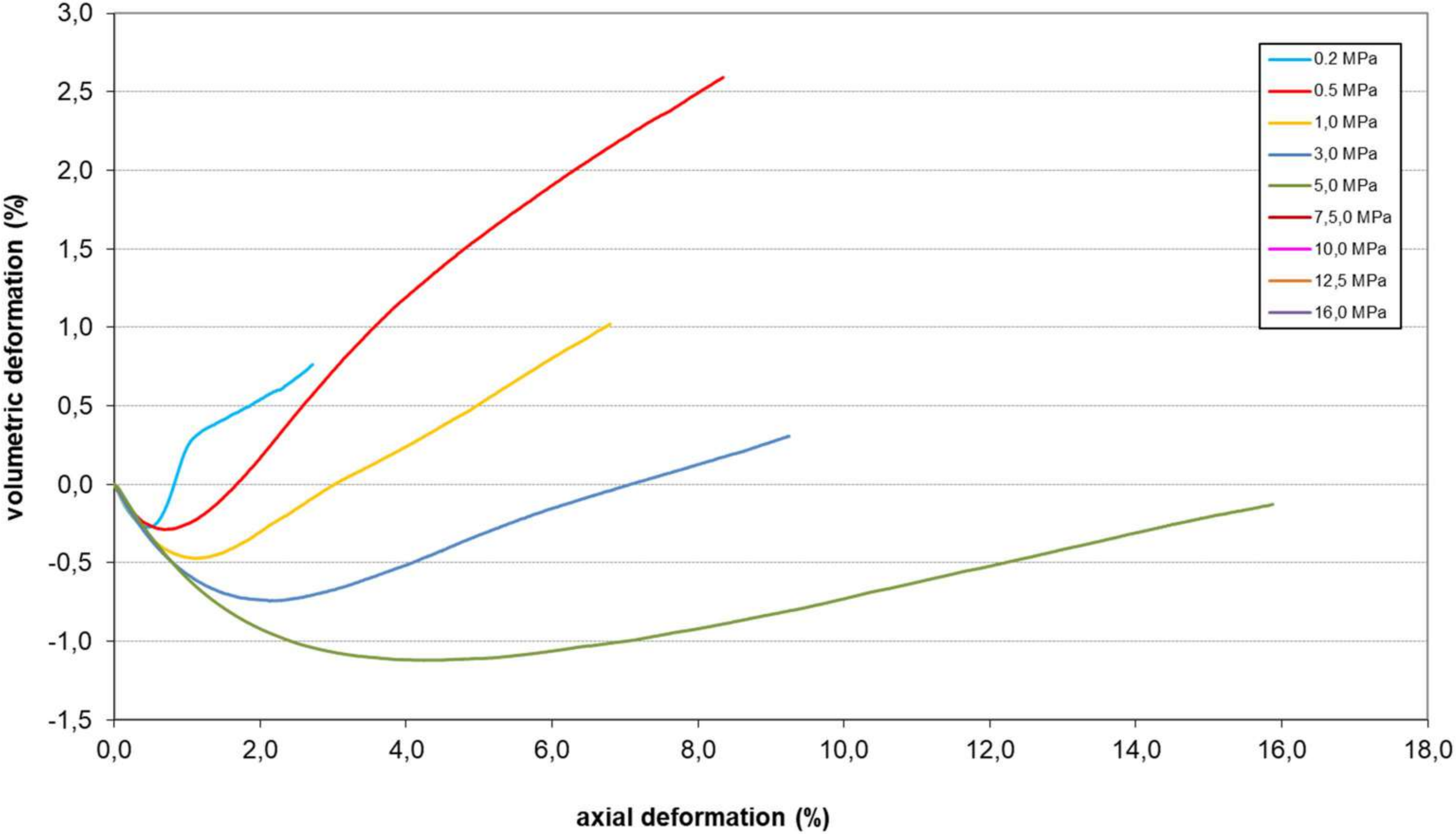
Triaxial strength tests (TC_nat)

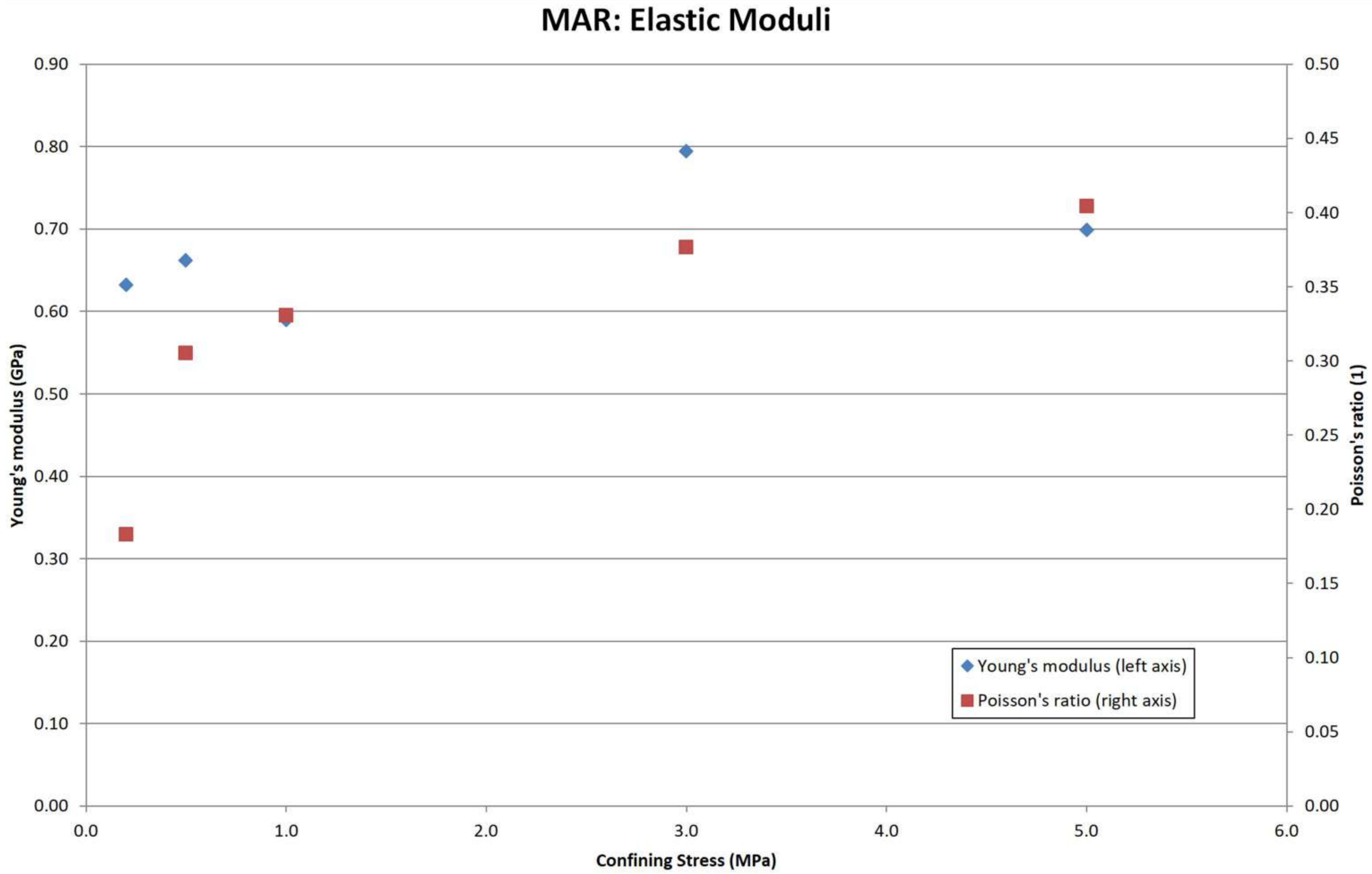
Unit – MAR (Marituba Arenito)

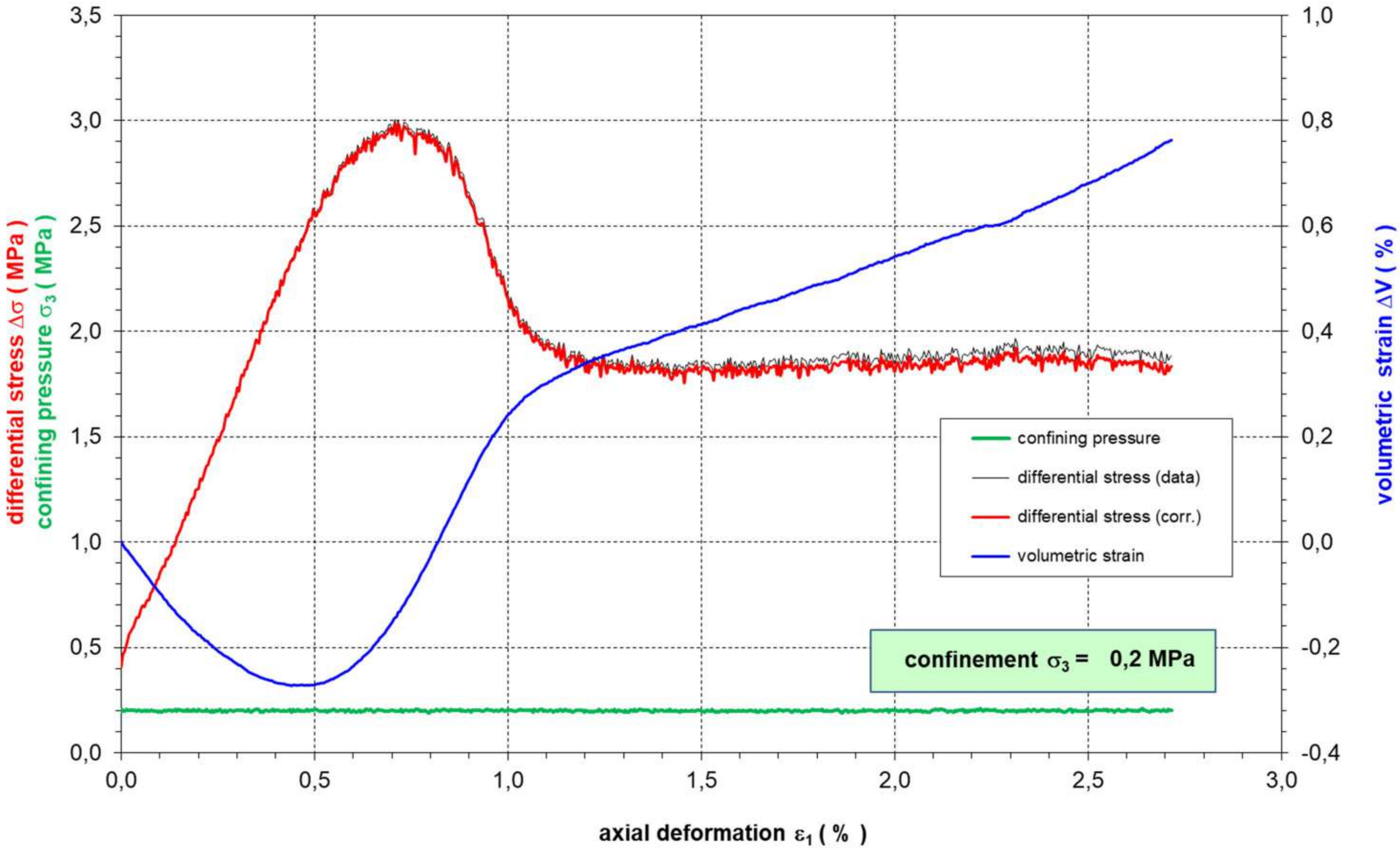
→ stress-strain curves of all tests

Appendix 10

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"


3,0
2,5
2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
volumetric deformation (%)
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
16,0
18,0
axial deformation (%)
0.2 MPa
0.5 MPa
1,0 MPa
3,0 MPa
5,0 MPa
7,5,0 MPa
10,0 MPa
12,5 MPa
16,0 MPa


MAR: Elastic Moduli
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Young's modulus (GPa)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Poisson's ratio (1)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Confining Stress (MPa)
Young's modulus (left axis)
Poisson's ratio (right axis)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

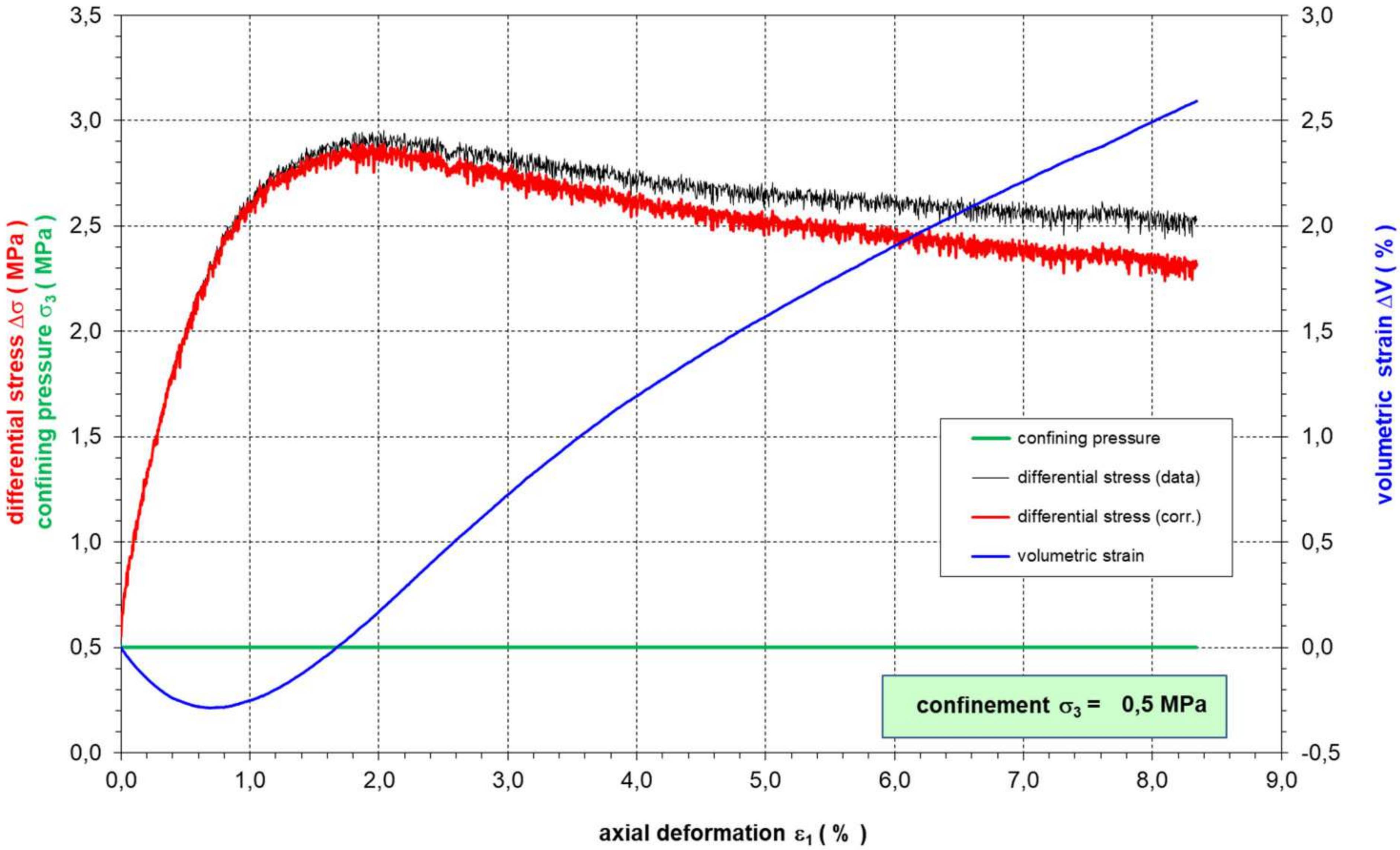
Triaxial strength test (TC_nat)

Unit – MAR (Marituba Arenito)

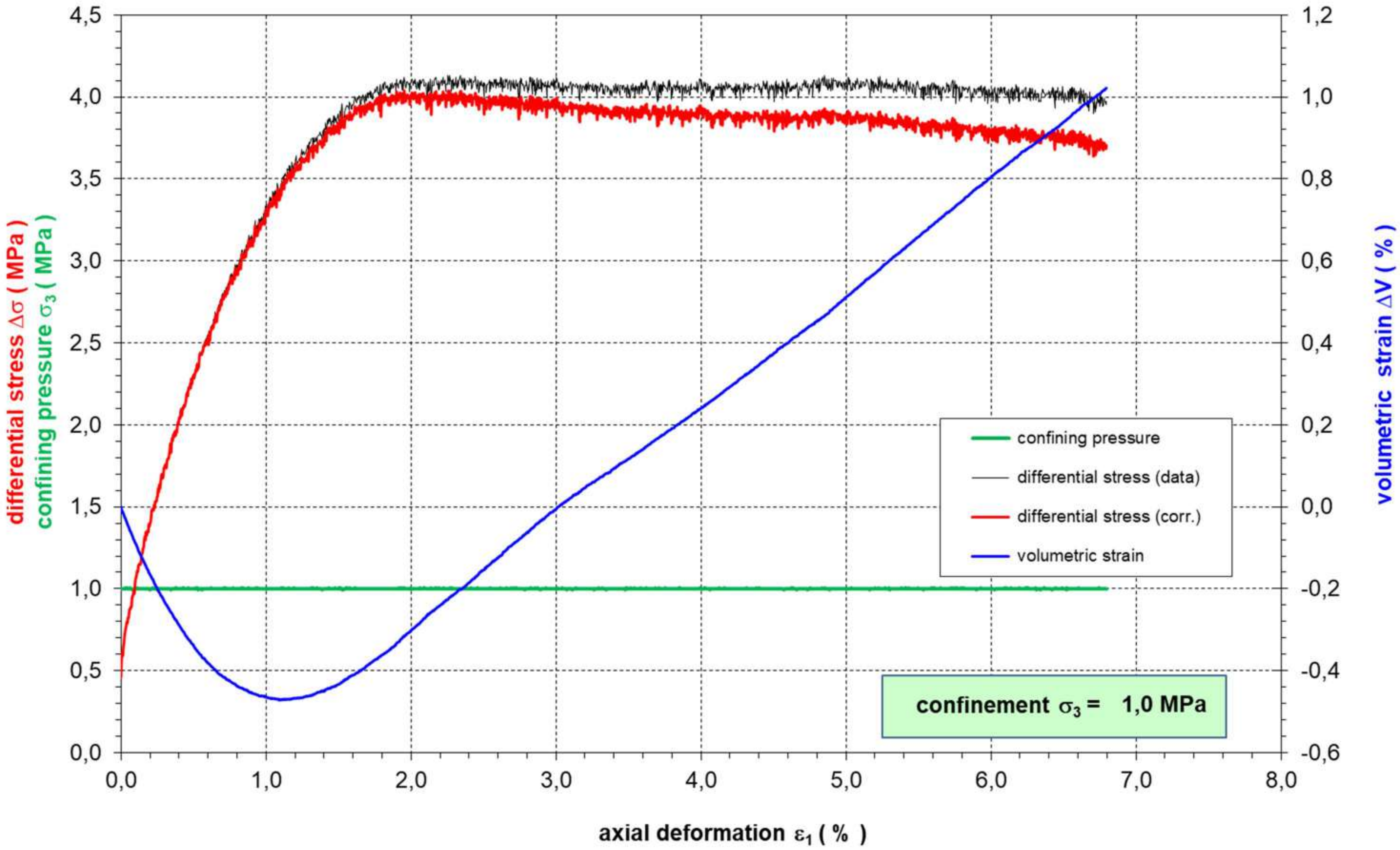
→ stress-strain behavior; sample 743/MAR003/TC_d1

Appendix 13

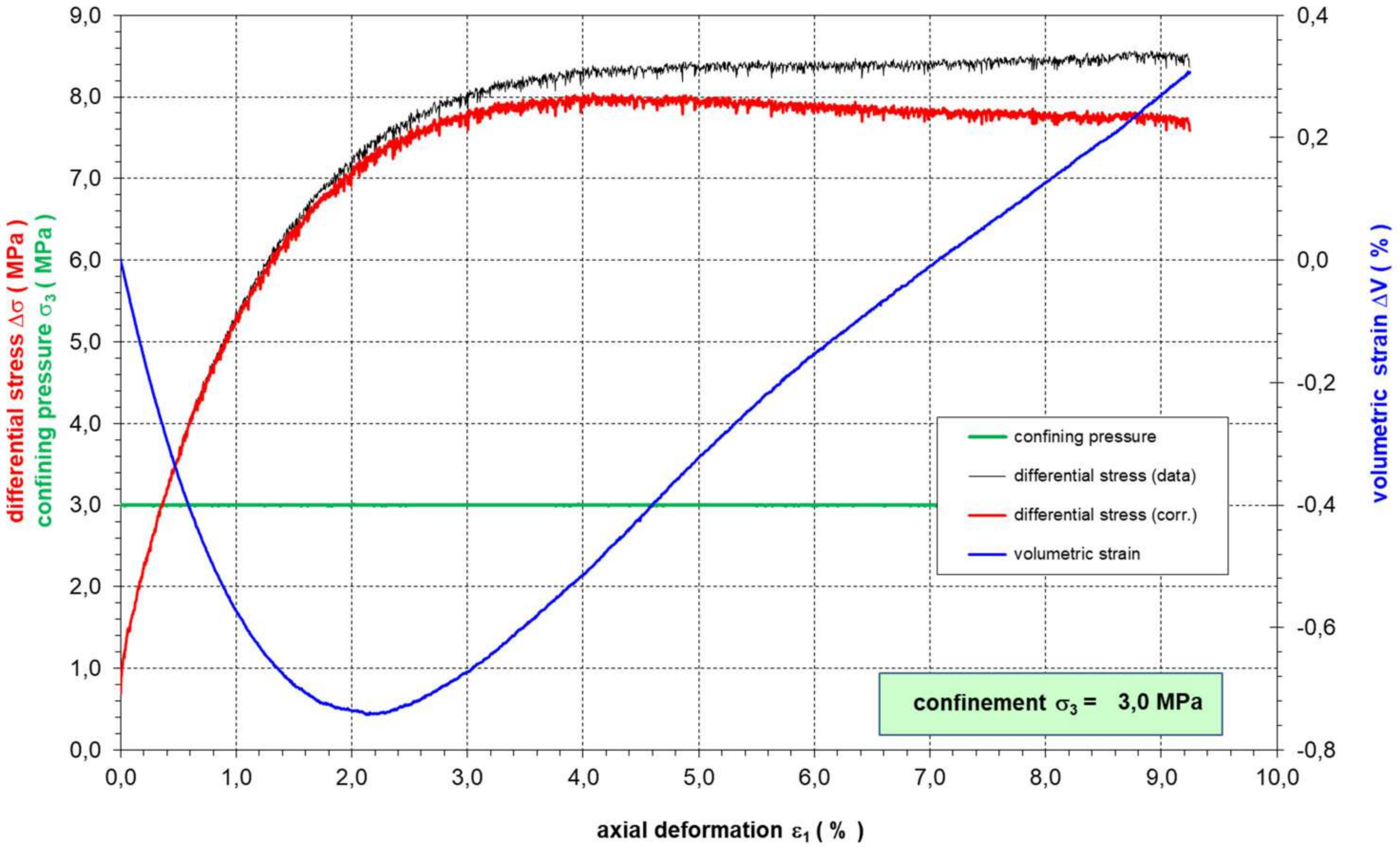
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



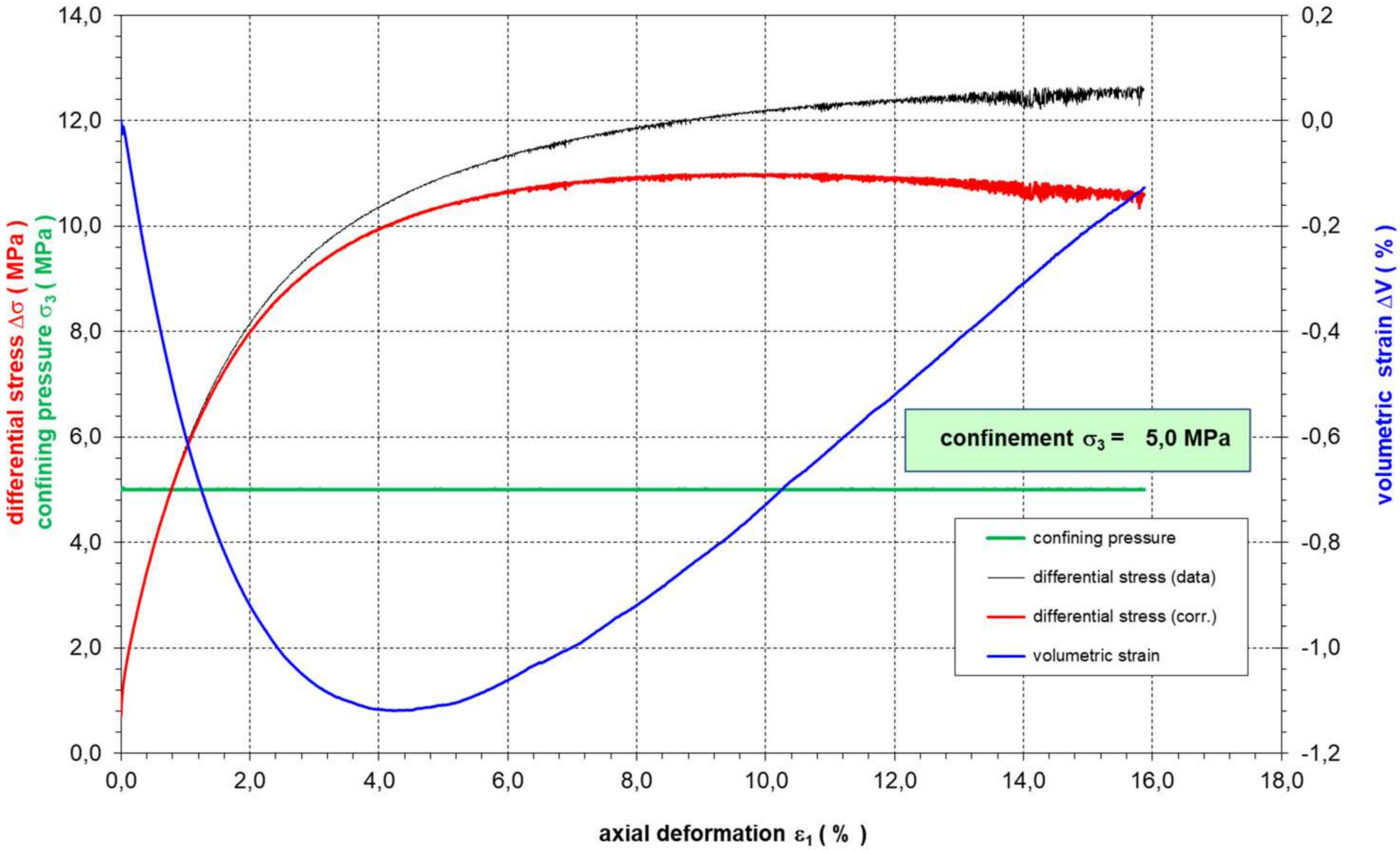
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
-0,5
volumetric strain ΔV (%)
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 0,5 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength test (TC_nat)** **Unit – MAR (Marituba Arenito)** → stress-strain behavior; sample 743/MAR028/TC_d3	**Appendix 15** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength test (TC_nat)** **Unit – MAR (Marituba Arenito)** → stress-strain behavior; sample 743/MAR029/TC_d4	**Appendix 16** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – MAR (Marituba Arenito)

→ stress-strain behavior; sample 743/MAR029/TC_d5

Appendix 17

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	**9**	**9**		**6**	**6**		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

Overview of planned tests

Unit – MAG (Marituba Argilito)

Appendix 18

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

IfG - Lab-No.	743/MAG001/TC_d1	743/MAG002/TC_d2	743/MAG002/TC_d3	743/MAG003/TC_d4
Rock Type / Unit	MAG	MAG	MAG	MAG
Sample	MAG_001	MAG_002	MAG_002	MAG_003
Depth (m)				
Length l (mm) =	200.765	199.788	200.905	192.140
Diameter d (mm) =	94.380	94.625	93.667	96.613
Ratio l_o/d_o =	2.13	2.11	2.14	1.99
Mass M (g) =	2747.80	2772.6	2826.2	2791.1
Area A (cm^2) =	69.960	70.324	68.907	73.310
Volume V (cm^3) =	1404.55	1404.98	1384.38	1408.57
Density ρ (g/cm^3) =	1.956	1.973	2.041	1.982
US L (h) - p	-	-	-	-
US Q1 (a/c) - p	-	-	-	-
US Q2 (b/d) - p	-	-	-	-
US L (h) - s	-	-	-	-
US L (h) - p(s)	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-
E_d (GPa) =	-	-	-	-
K_d (GPa) =	-	-	-	-
G_d (GPa) =	-	-	-	-
ν_d =	-	-	-	-
	TC	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.5	1.0	3.0	5.0
σ_{Dil} (MPa) =	3.0	3.5	7.3	8.3
ΔV_{Dil} (%) =	-0.19	-0.27	-0.72	-2.31
ε_{Dil} (%) =	0.57	0.68	1.94	10.92
σ_{Fail} (MPa) =	3.2	3.5	7.4	9.1
ΔV_{Fail} (%) =	-0.16	-0.26	-0.70	-2.10
ε_{Fail} (%) =	0.71	0.84	1.66	5.99
σ_{1Fail} (MPa) =	3.70	4.47	10.44	14.07
α (°) =	65	65	65	65
σ_n (MPa) =	1.07	1.62	4.33	6.62
τ (MPa) =	1.23	1.33	2.85	3.47
ϕ=	**24.2**			
C=	**0.8**			

BEFORE:

AFTER:

σ_3 = 0.5 MPa

σ_3 = 1.0 MPa

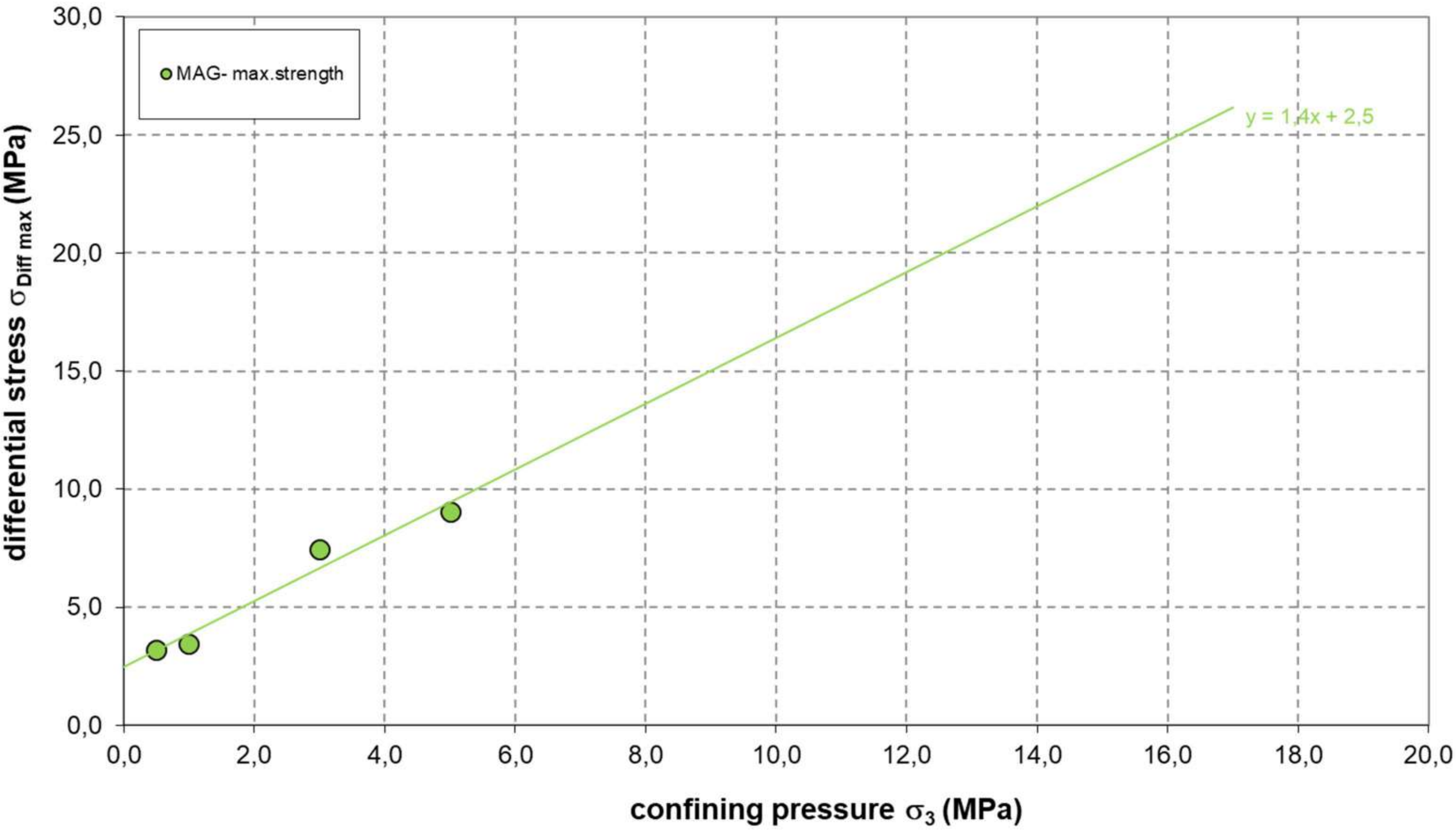
σ_3 = 3.0 MPa

σ_3 = 5.0 MPa

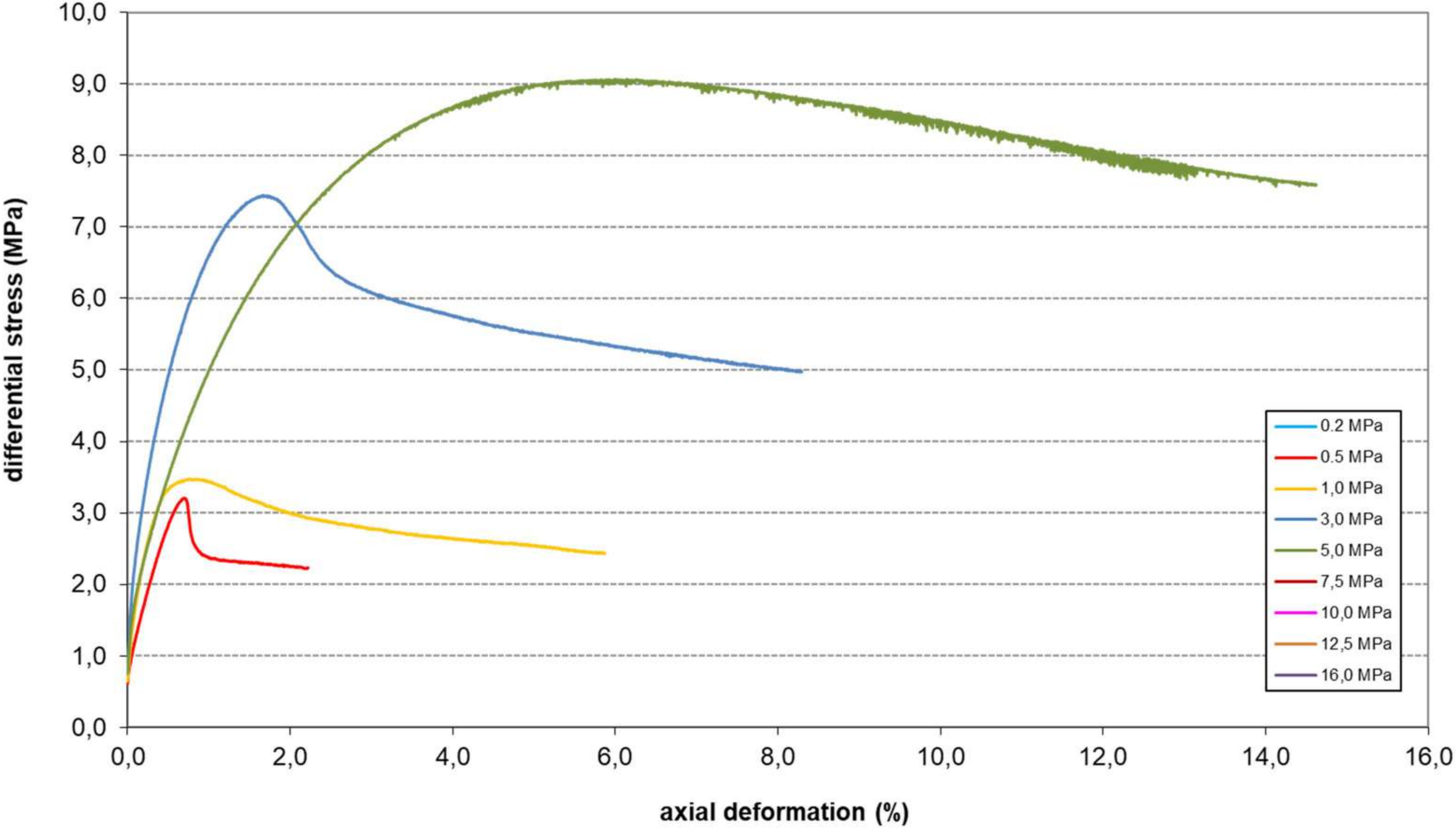
Samples for triaxial strength tests (TC_nat)

Unit – MAG (Marituba Argilito)

→ photo-documentation before and after the test



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH	**Triaxial strength tests (TC_nat)** **Unit – MAG (Marituba Argilito)** → maximum strength values dependent on the radial stress	**Appendix 21** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



INSTITUT FÜR GEBIRGSMECHANIK GMBH

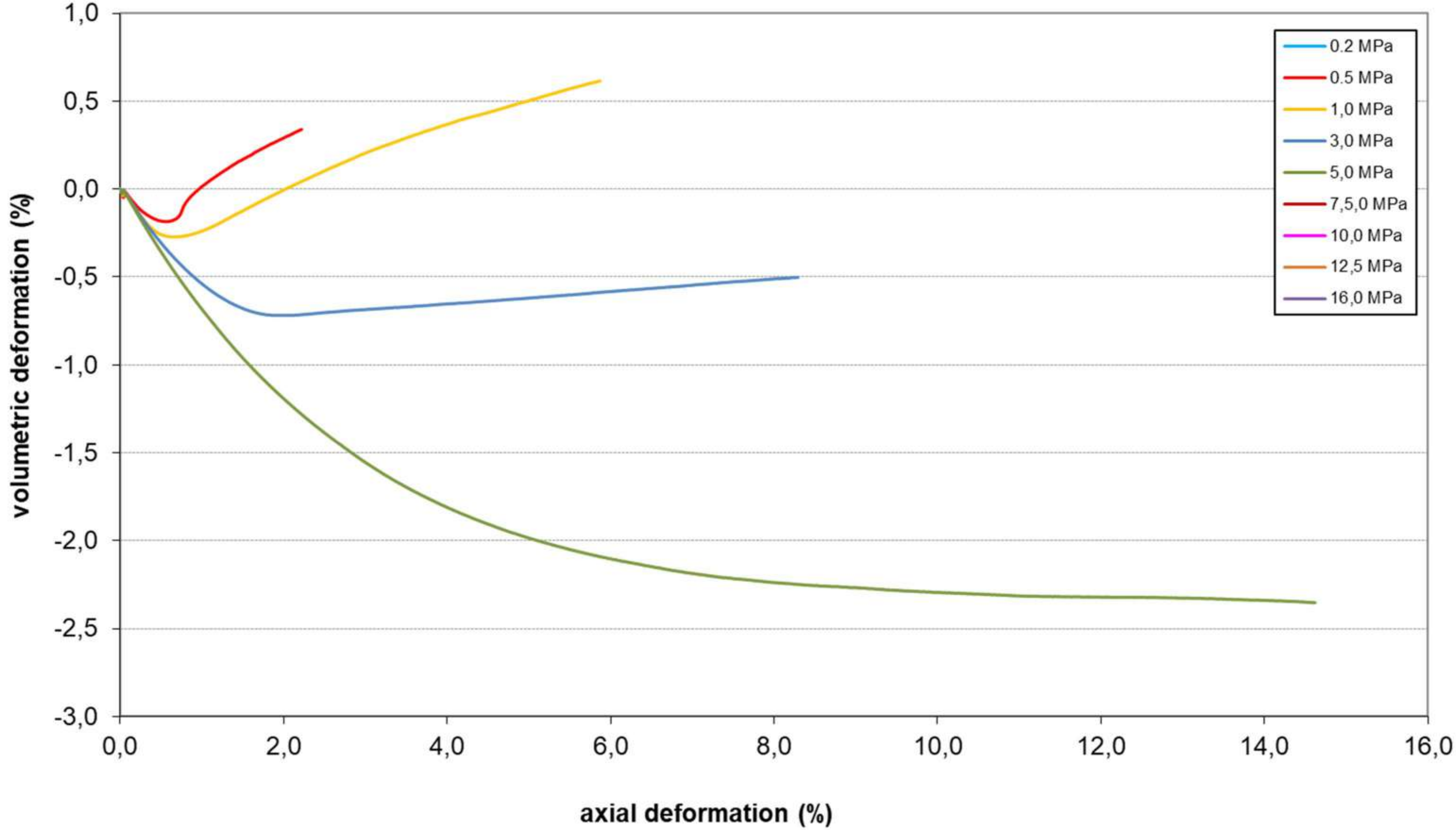
Triaxial strength tests (TC_nat)

Unit – MAR (Marituba Argilito)

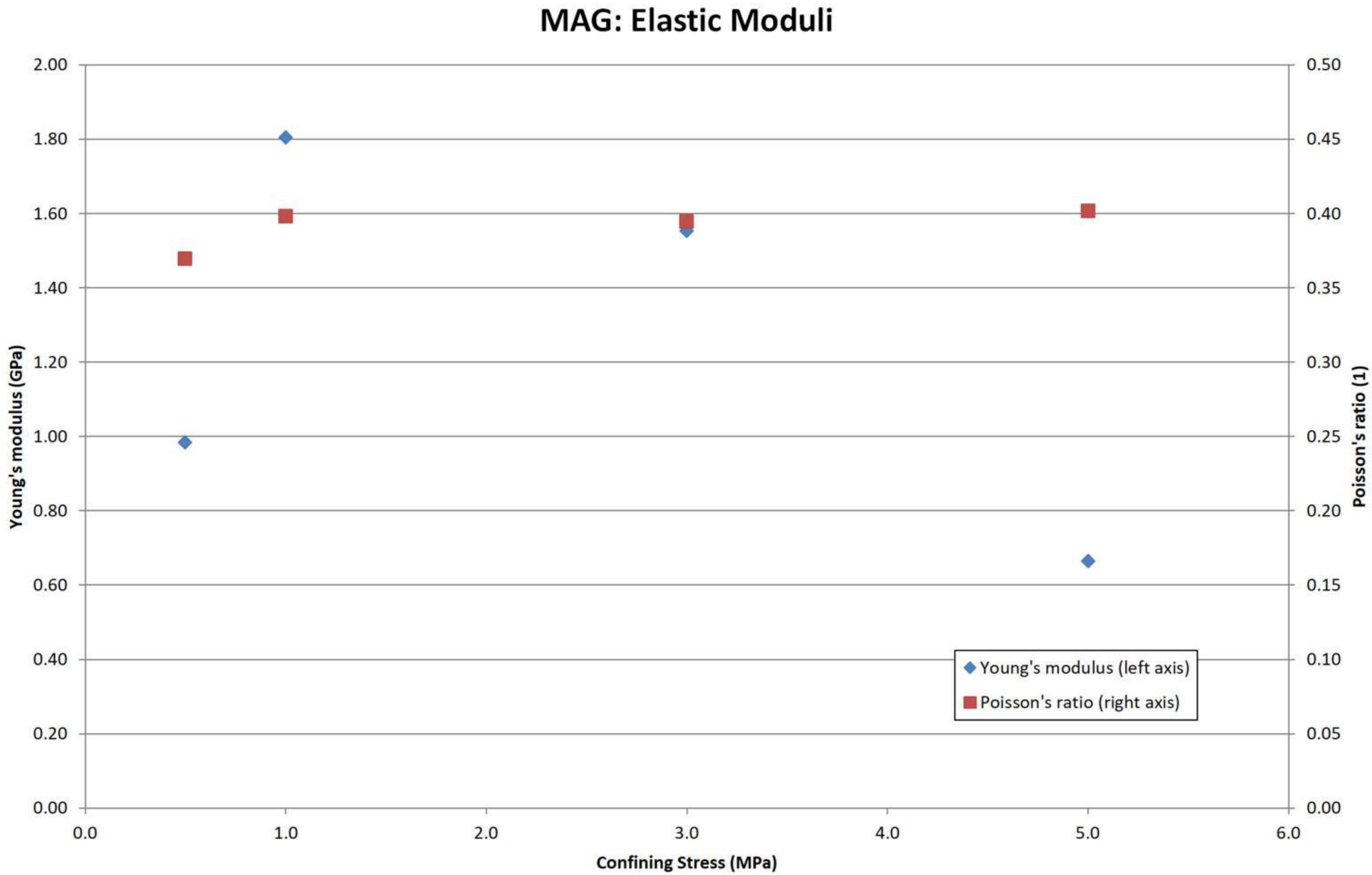
→ stress-strain curves of all tests

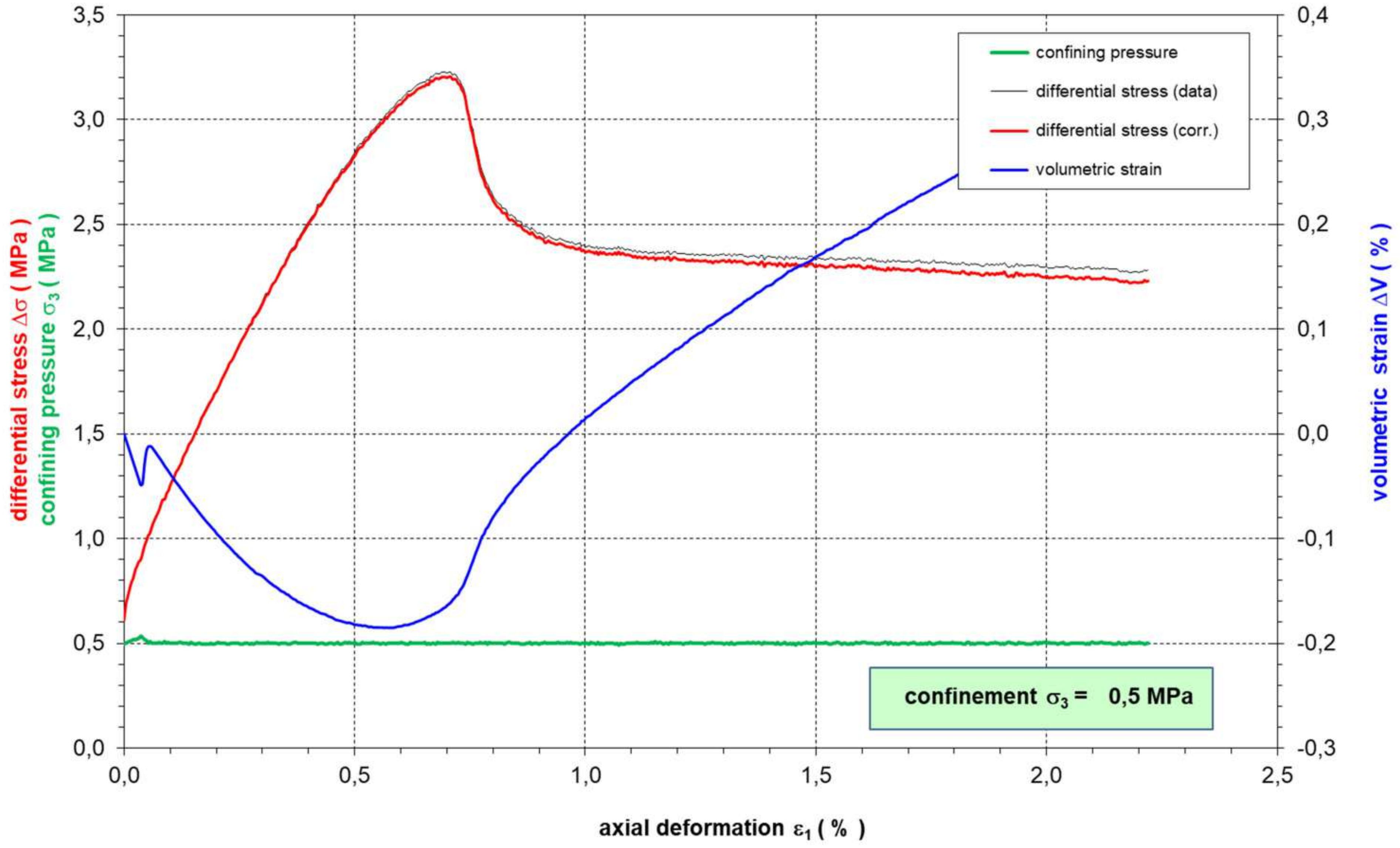
Appendix 22

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
-2,5
-3,0
volumetric deformation (%)
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
16,0
axial deformation (%)
0.2 MPa
0.5 MPa
1,0 MPa
3,0 MPa
5,0 MPa
7,5,0 MPa
10,0 MPa
12,5 MPa
16,0 MPa


MAG: Elastic Moduli
Young's modulus (GPa)
Poisson's ratio (1)
Confining Stress (MPa)
Young's modulus (left axis)
Poisson's ratio (right axis)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
1.0
2.0
3.0
4.0
5.0
6.0



INSTITUT FÜR GEBIRGSMECHANIK GMBH

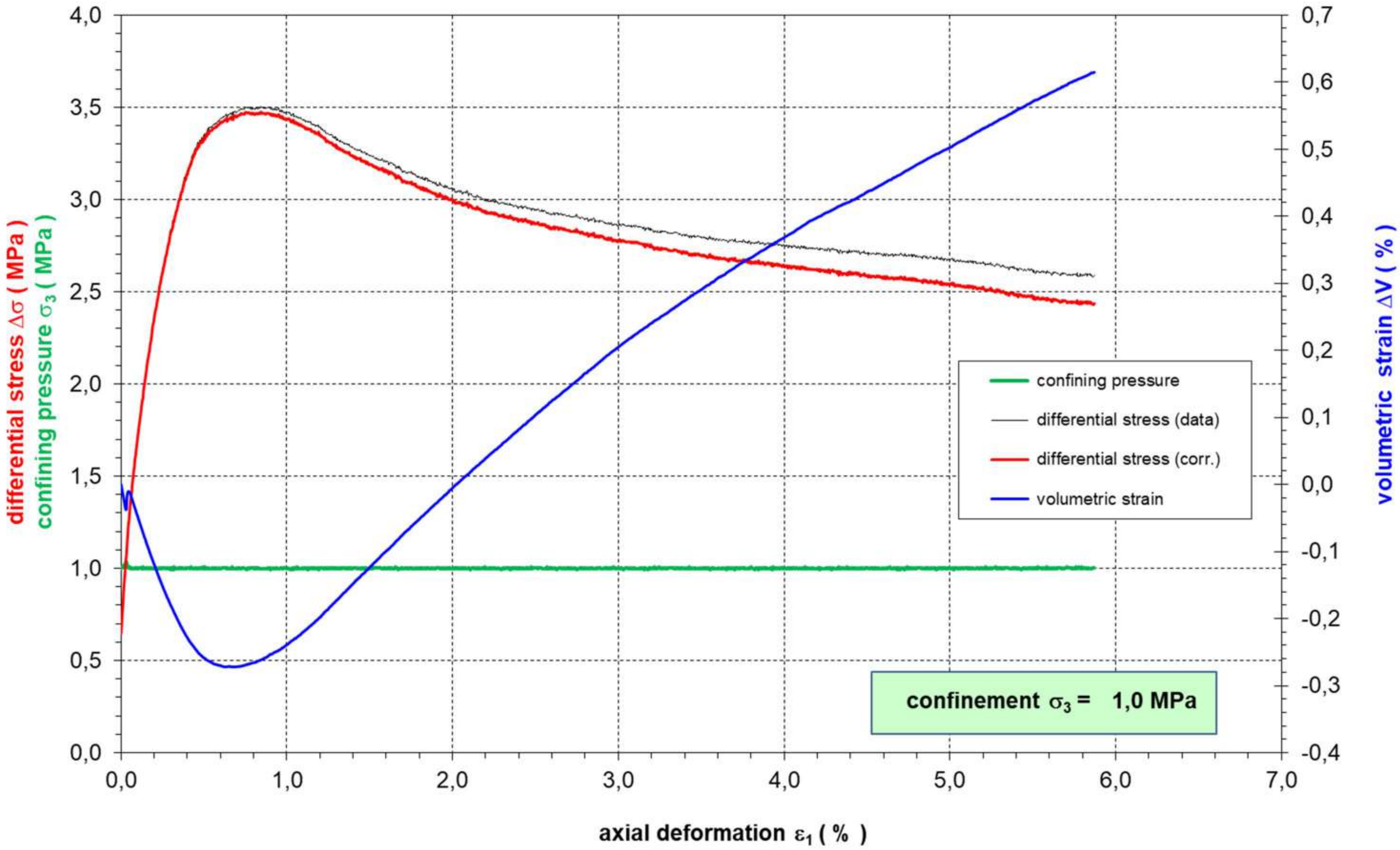
Triaxial strength test (TC_nat)

Unit – MAR (Marituba Argilito)

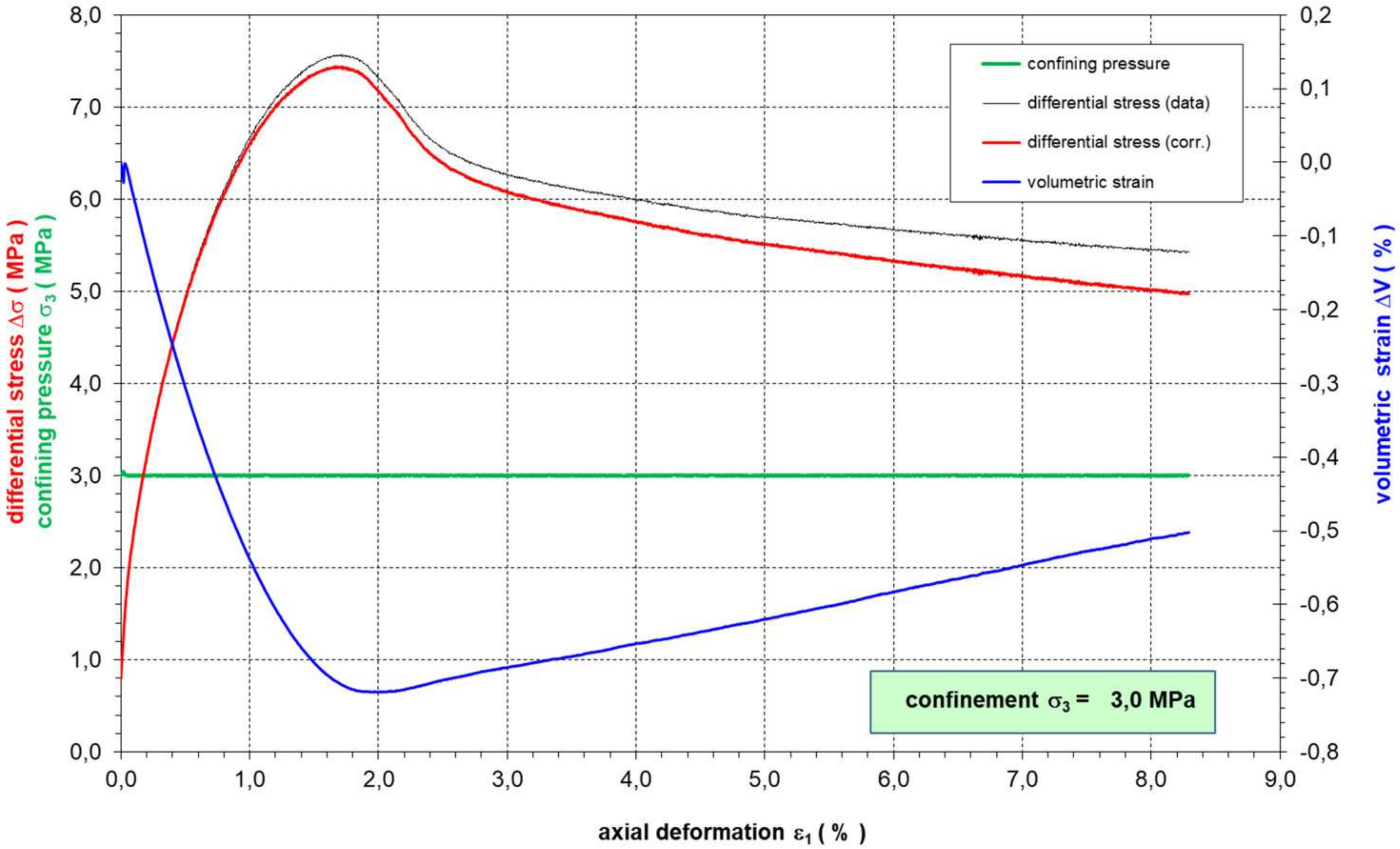
→ stress-strain behavior; sample 743/MAG001/TC_d1

Appendix 25

B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”



4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
-0,1
-0,2
-0,3
-0,4
volumetric strain ΔV (%)
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 1,0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

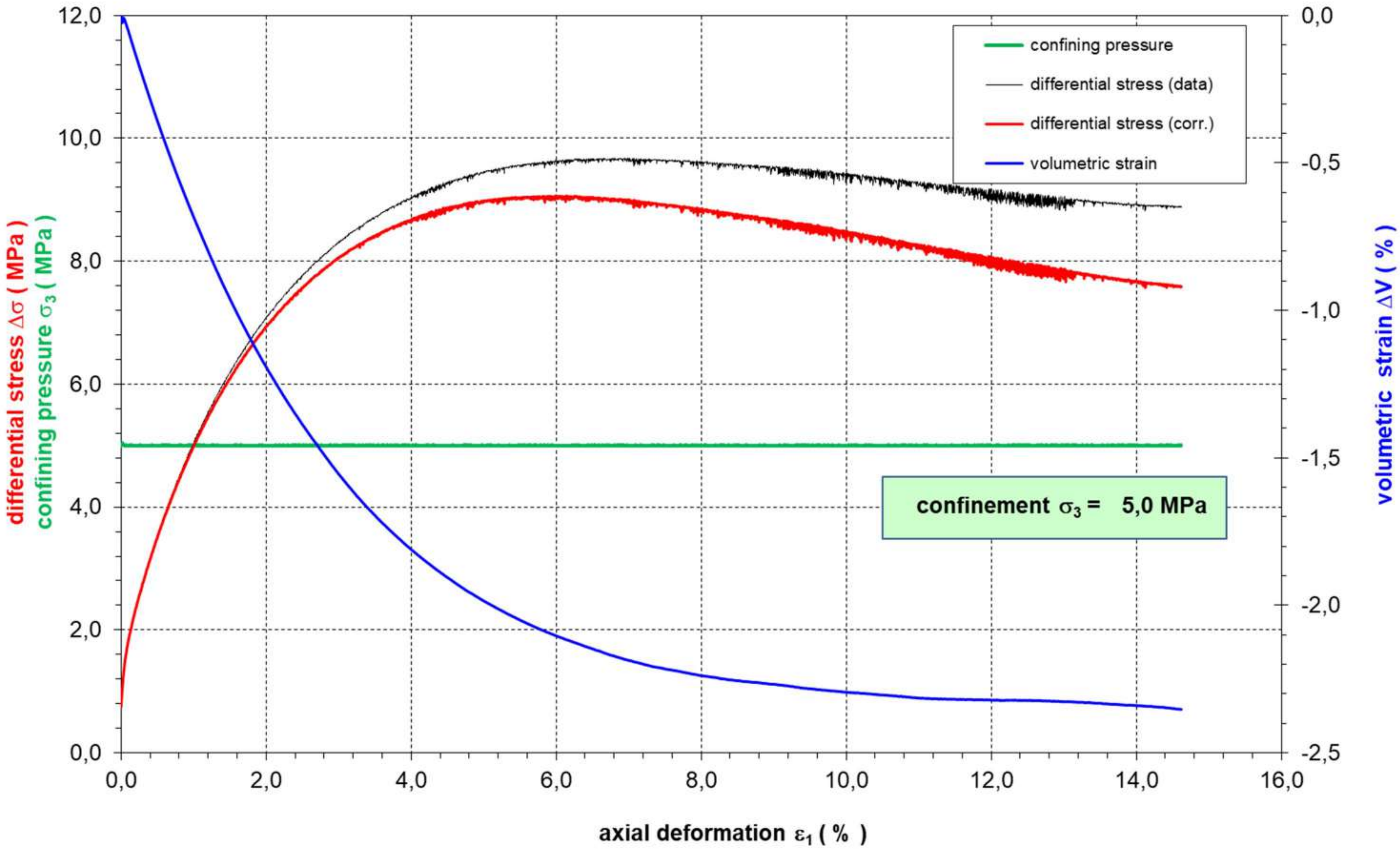
Triaxial strength test (TC_nat)

Unit – MAR (Marituba Argilito)

→ stress-strain behavior; sample 743/MAR002/TC_d3

Appendix 27

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – MAR (Marituba Argilito)

→ stress-strain behavior; sample 743/MAG003/TC_d4

Appendix 28

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	**9**	**9**		**6**	**6**		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/MOS002/TC_d1	743/MOS003/TC_d2	743/MOS005/TC_d3	743/MOS008/TC_d4	743/MOS017/TC_d5	743/MOS017/TC_d6
Rock Type / Unit	MOS	MOS	MOS	MOS	MOS	MOS
Sample	MOS_002	MOS_003	MOS_005	MOS_008	MOS_017	MOS_017
Depth (m)						
Length l (mm) =	189.768	200.338	199.635	198.030	192.375	180.378
Diameter d (mm) =	100.092	99.34	99.462	99.835	100.283	96.600
Ratio l_o/d_o =	1.90	2.02	2.01	1.98	1.92	1.87
Mass M (g) =	3589.10	3179.0	3332.4	3527.0	3049.5	2764.7
Area A (cm^2) =	78.684	77.507	77.697	78.281	78.985	73.290
Volume V (cm^3) =	1493.18	1552.75	1551.10	1550.20	1519.47	1321.99
Density ρ (g/cm^3) =	2.404	2.047	2.148	2.275	2.007	2.091
US L (h) - p	-	-	-	-	-	-
US Q1 (a/c) - p	-	-	-	-	-	-
US Q2 (b/d) - p	-	-	-	-	-	-
US L (h) - s	-	-	-	-	-	-
US L (h) - p(s)	-	-	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-	-
E_d (GPa) =	-	-	-	-	-	-
K_d (GPa) =	-	-	-	-	-	-
G_d (GPa) =	-	-	-	-	-	-
ν_d =	-	-	-	-	-	-
	TC	**TC**	**TC**	**TC**	**TC**	**UC**
Temp. (°C)	**23**	**23**	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.5	1.0	3.0	5.0	0.5	3.0
σ_{Dil} (MPa) =	15.6	8.5	10.7	22.6	5.0	10.4
ΔV_{Dil} (%) =	-0.32	-0.27	-1.17	-0.16	-0.17	-0.82
ε_{Dil} (%) =	0.45	0.76	5.50	0.44	0.29	6.16
σ_{Fail} (MPa) =	17.4	9.1	10.8	24.5	5.9	12.8
ΔV_{Fail} (%) =	-0.30	-0.25	-1.16	-0.15	-0.16	-0.29
ε_{Fail} (%) =	0.50	0.47	5.74	0.64	0.36	0.76
σ_{1Fail} (MPa) =	17.88	10.10	13.80	29.48	6.40	15.75
α (°) =	65	65	65	65	65	65
σ_n (MPa) =	3.60	2.63	4.93	9.37	1.55	5.28
τ (MPa) =	6.66	3.49	4.13	9.38	2.26	4.88
ϕ=	**33.2**					
C=	**2.2**					

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

Unit – MOS (Mosqueiro)

→ petrophysical parameters and stress-strain-values

Appendix 30

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:

AFTER:

σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 3.0 MPa

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

Unit – MOS (Mosqueiro)

→ photo-documentation before and after the test

Appendix 31

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:

AFTER:

σ_3 = 5.0 MPa	σ_3 = 0.5 MPa	σ_3 = 3.0 MPa

INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

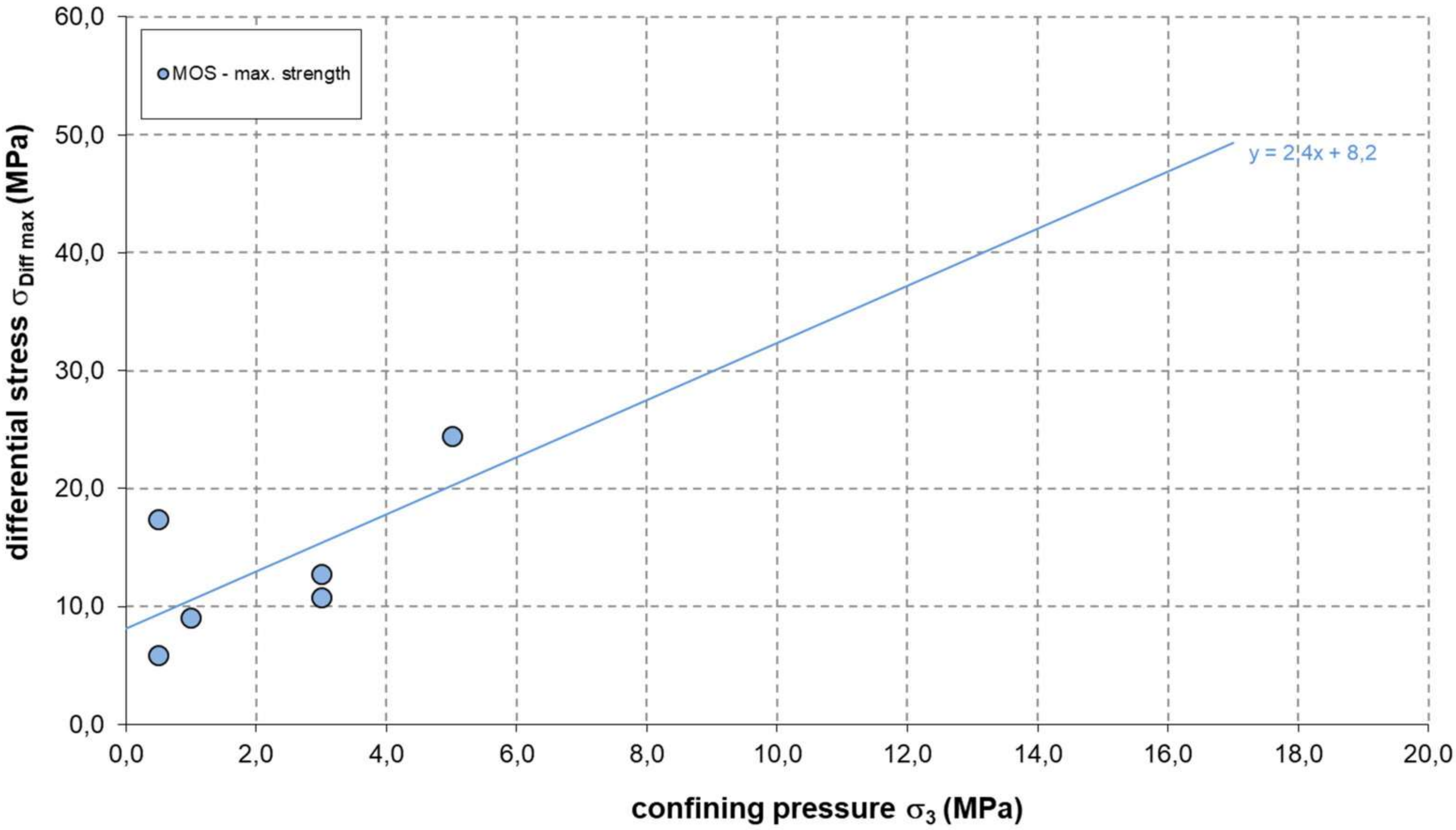
Samples for triaxial strength tests (TC_nat)

Unit – MOS (Mosqueiro)

→ photo-documentation before and after the test

Appendix 32

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

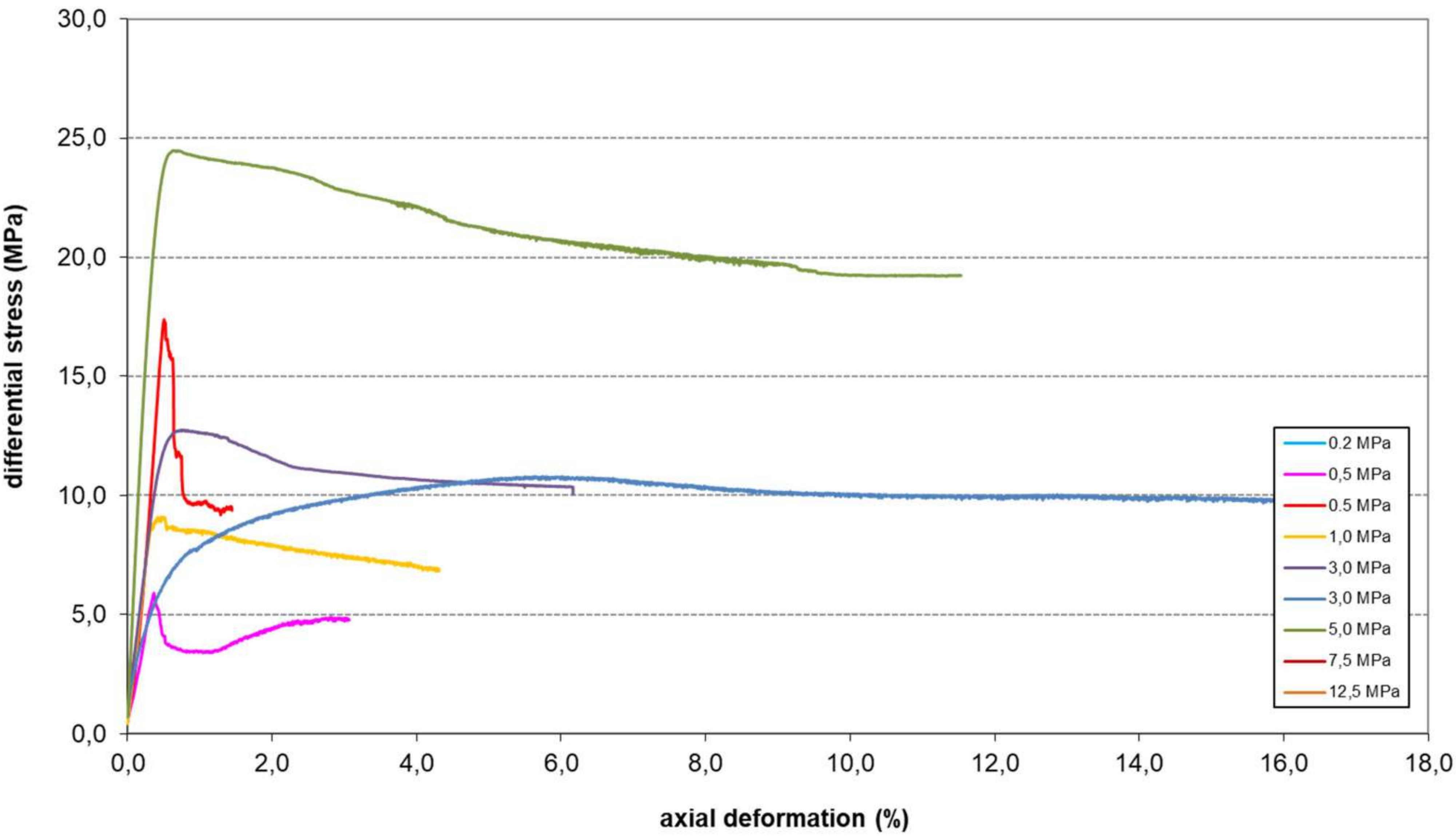
Triaxial strength tests (TC_nat)

Unit – MOS (Mosqueiro)

→ maximum strength values dependent on the radial stress

Appendix 33

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

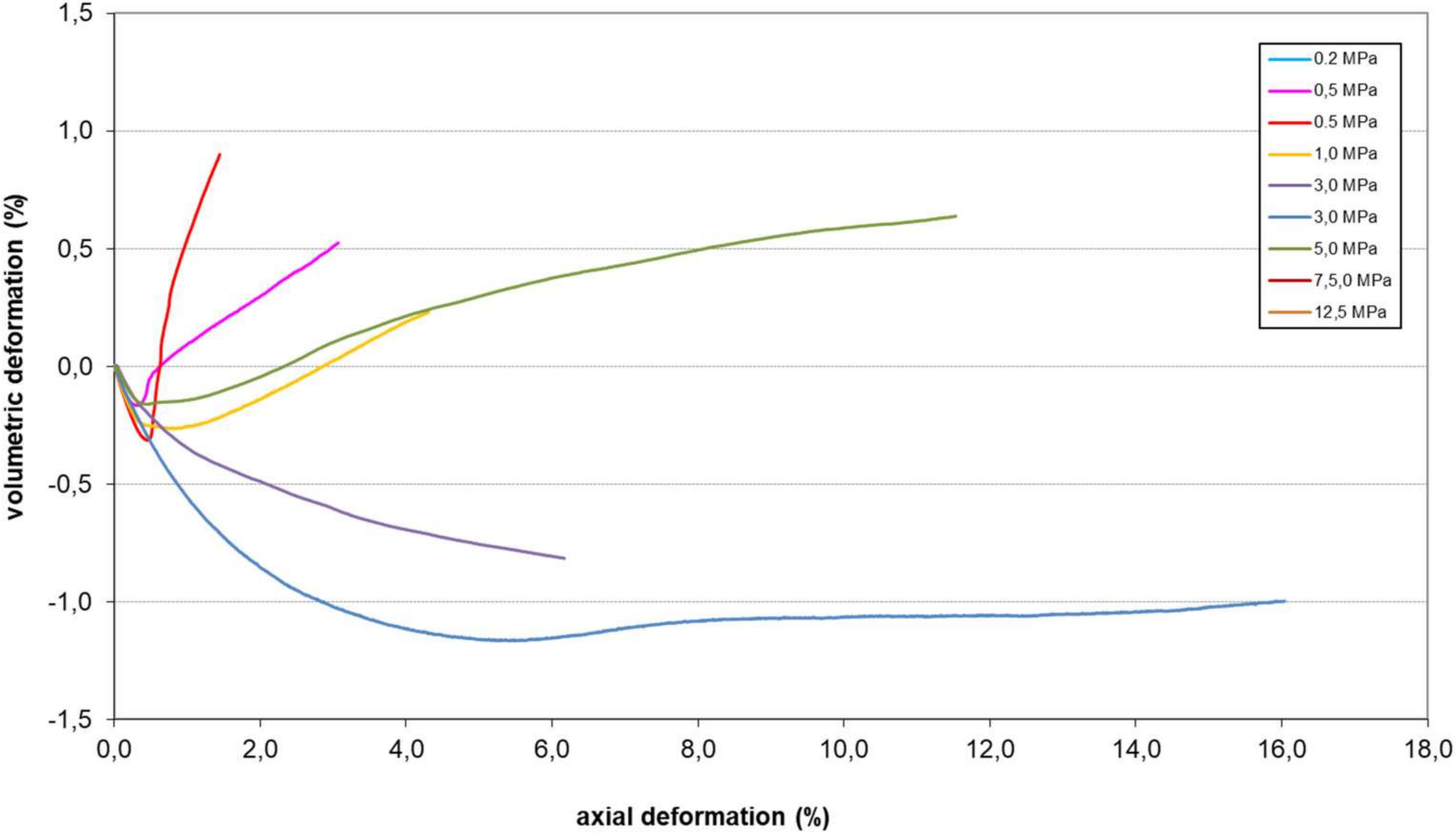
Triaxial strength tests (TC_nat)

Unit – MOS (Mosqueiro)

→ stress-strain curves of all tests

Appendix 34

B IfG 22/2021
“Rock Mechanical Investigations – Maceio – BRASKEM”



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

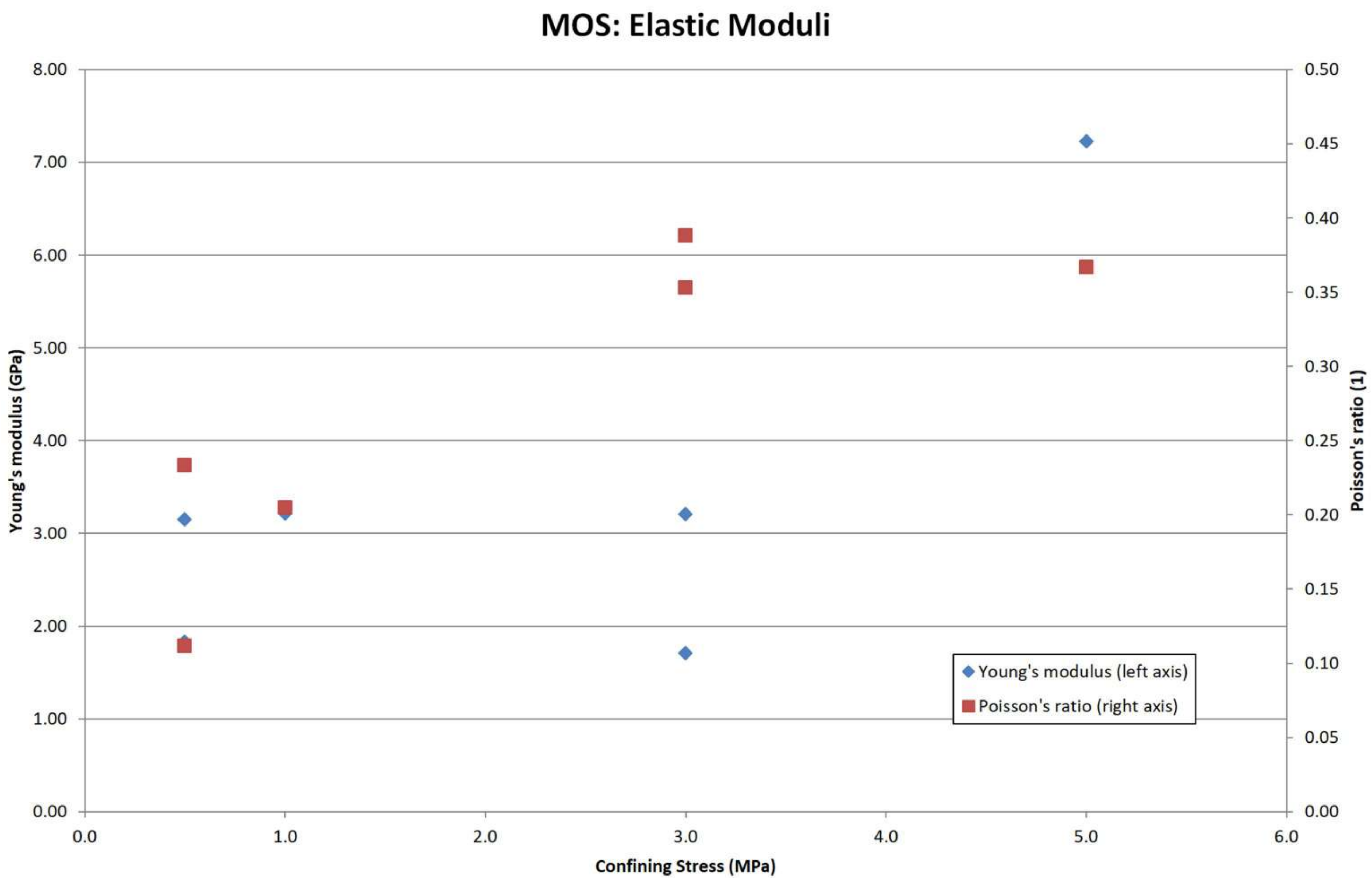
Triaxial strength tests (TC_nat)

Unit – MOS (Mosqueiro)

→ volumetric strain vs. axial deformation; dilatancy curves

Appendix 35

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

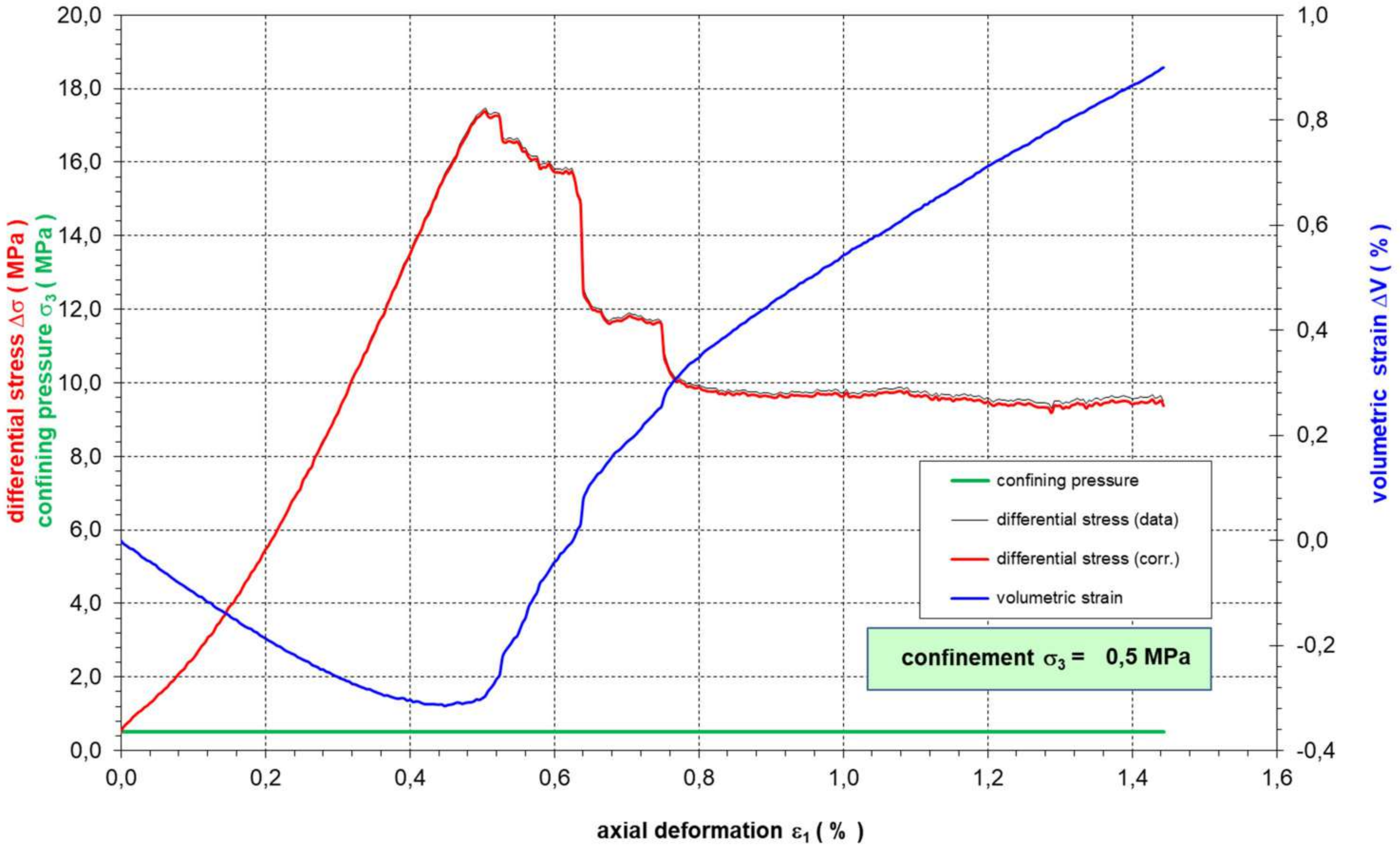
Triaxial strength tests (TC_nat)

Unit – MOS (Mosqueiro)

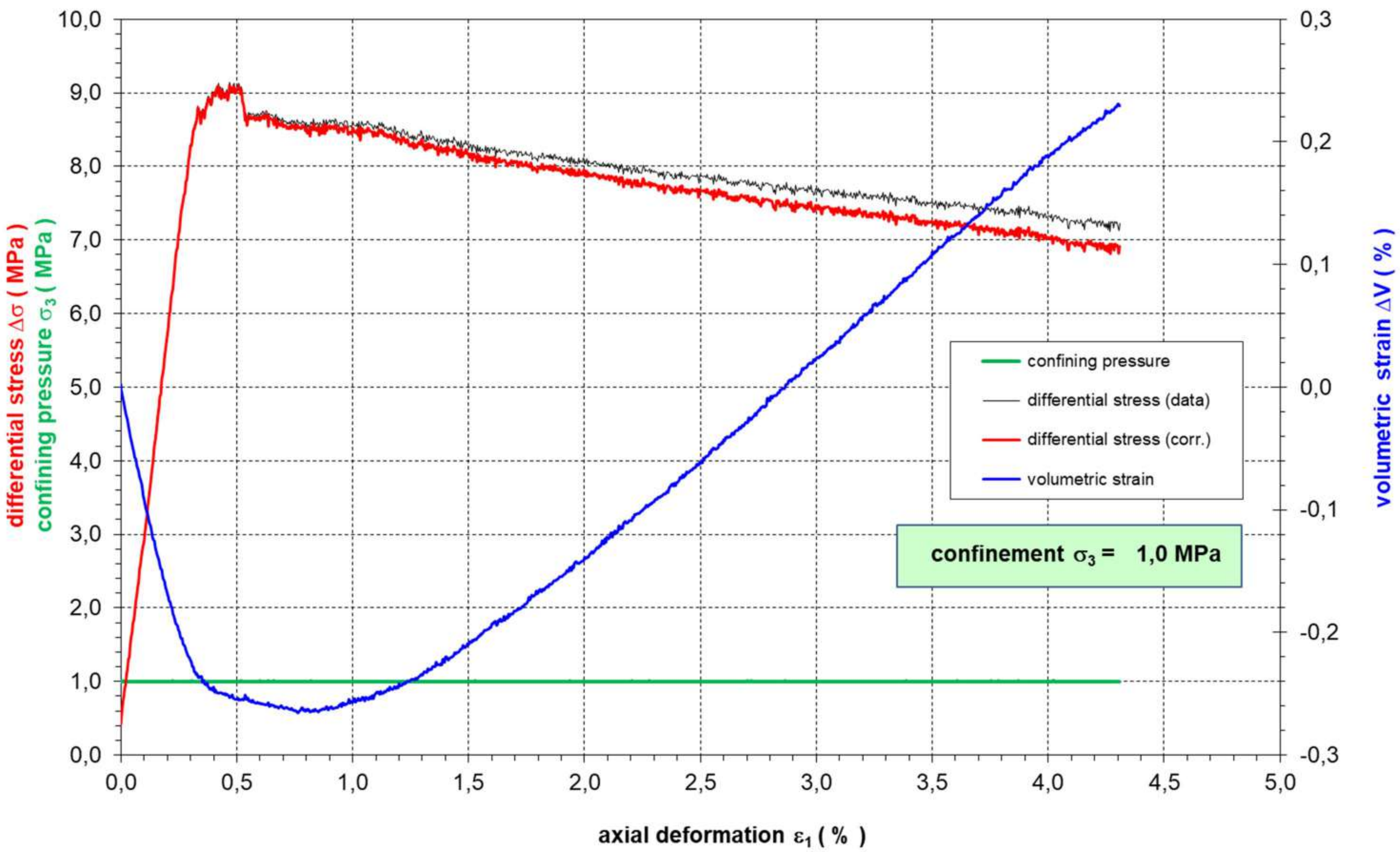
→ elastic parameters vs. confining stress

Appendix 36

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
20,0
18,0
16,0
14,0
12,0
10,0
8,0
6,0
4,0
2,0
0,0
1,0
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 0,5 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

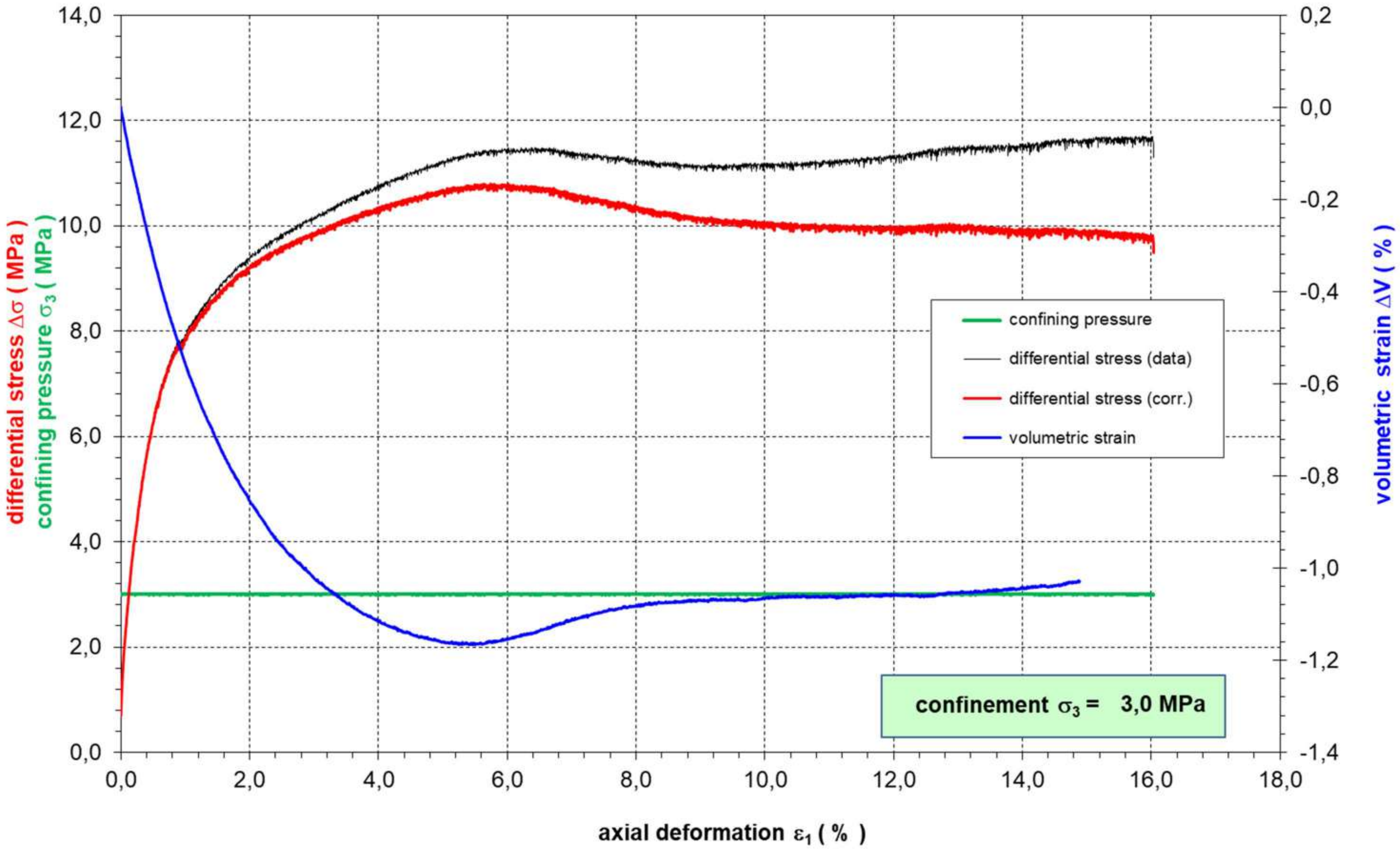
Triaxial strength test (TC_nat)

Unit – MOS (Mosqueiro)

→ stress-strain behavior; sample 743/MOS002/TC_d2

Appendix 38

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

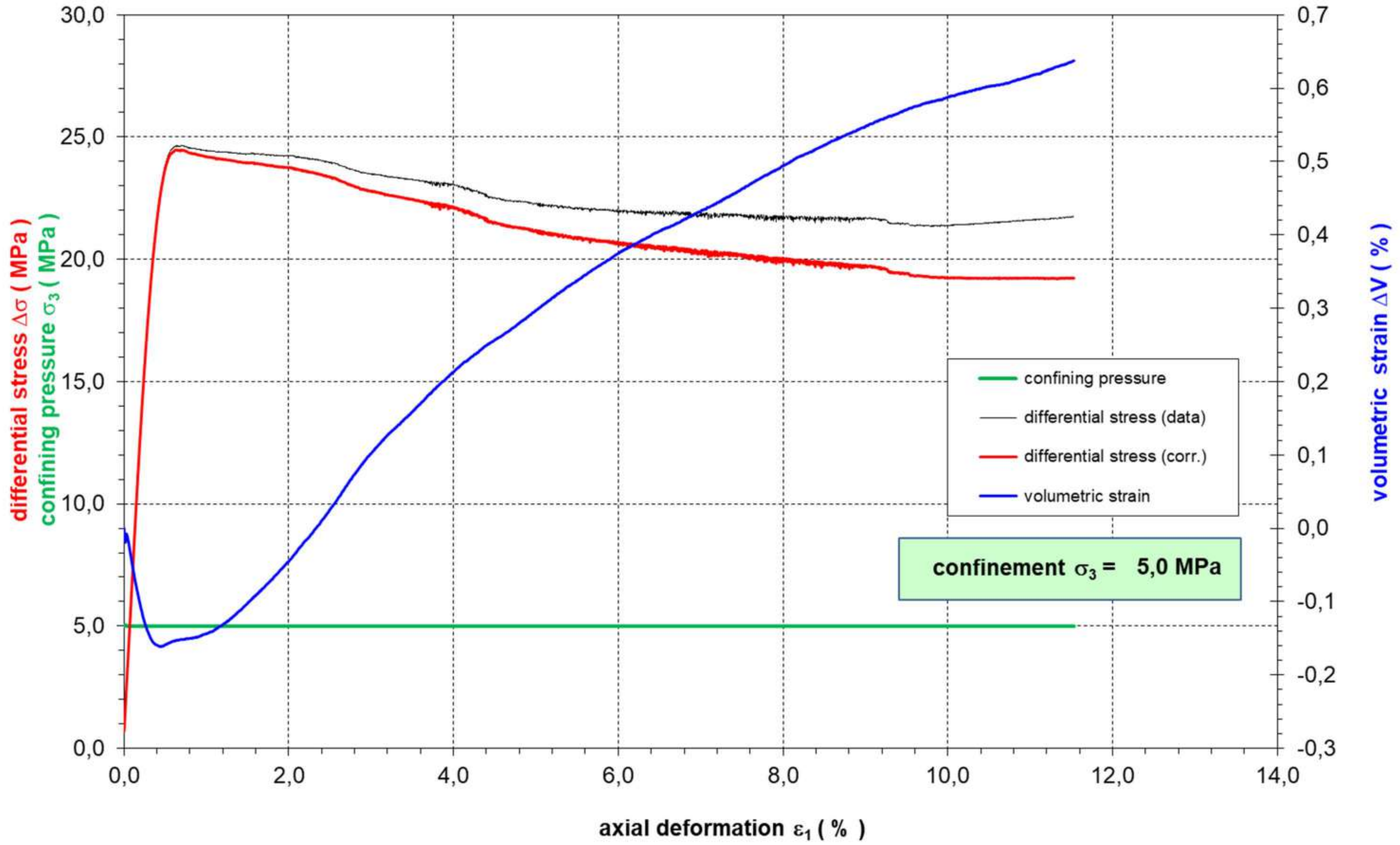
Triaxial strength test (TC_nat)

Unit – MOS (Mosqueiro)

→ stress-strain behavior; sample 743/MOS005/TC_d3

Appendix 39

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

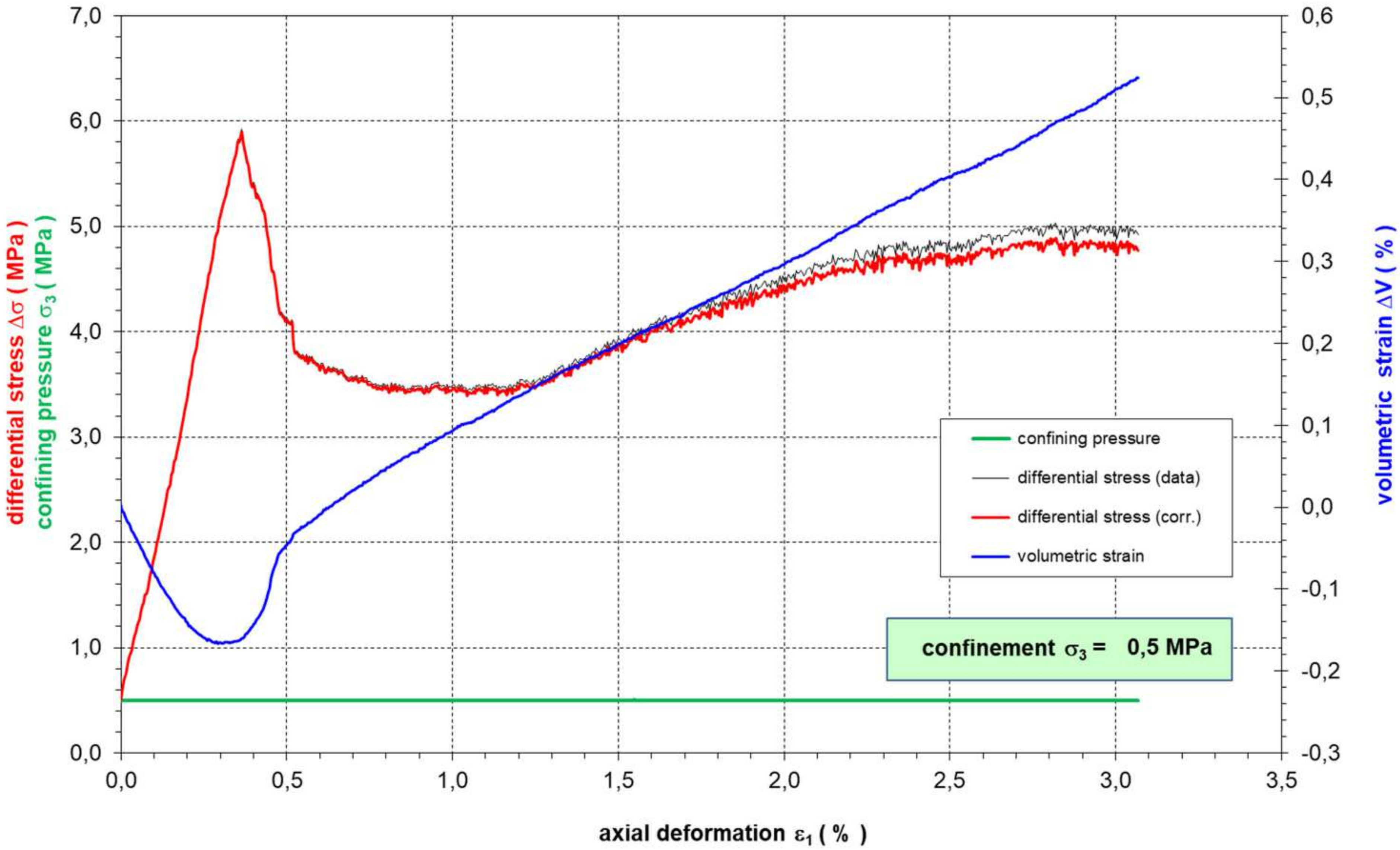
Triaxial strength test (TC_nat)

Unit – MOS (Mosqueiro)

→ stress-strain behavior; sample 743/MOS008/TC_d4

Appendix 40

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

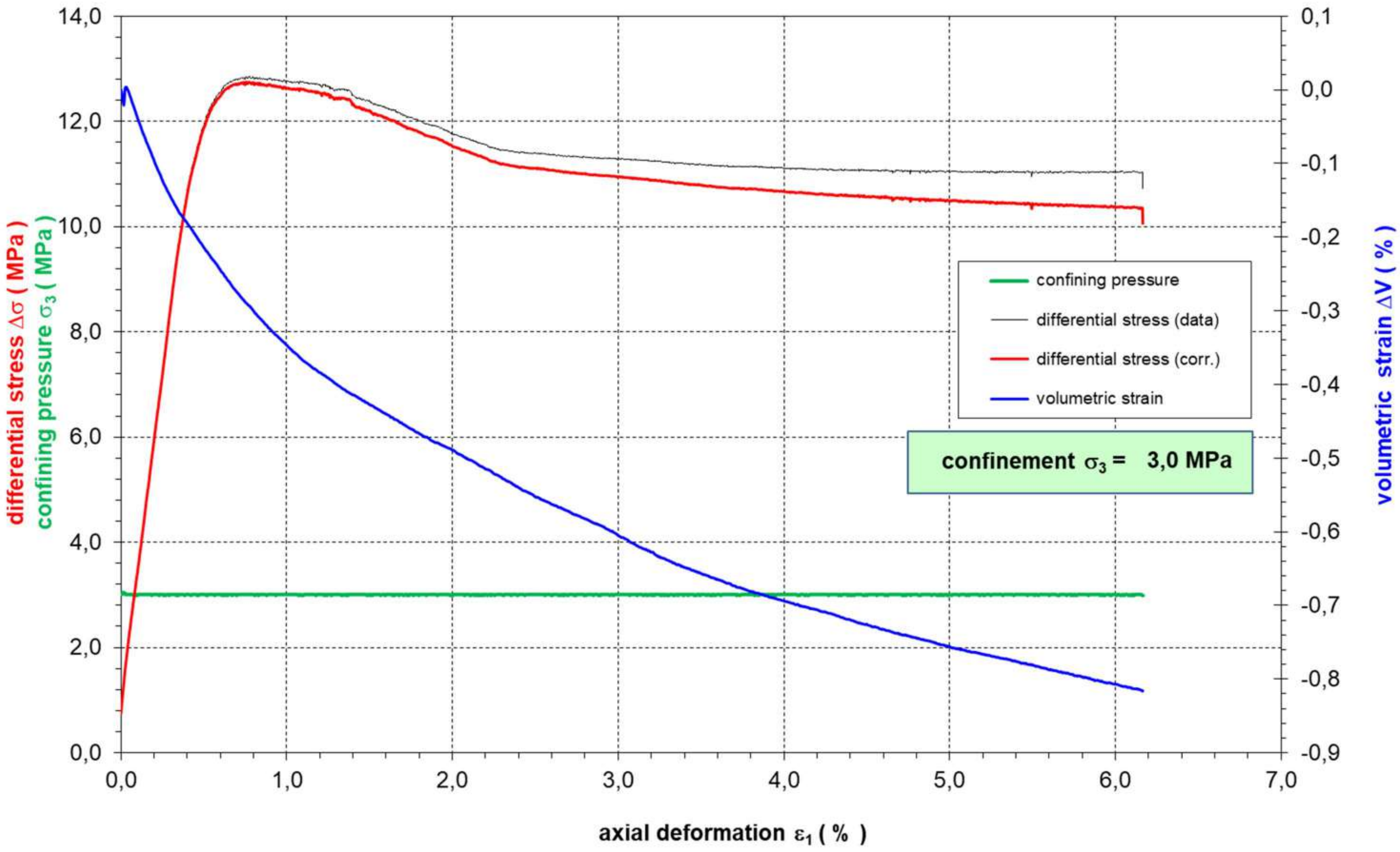
Triaxial strength test (TC_nat)

Unit – MOS (Mosqueiro)

→ stress-strain behavior; sample 743/MOS017/TC_d5

Appendix 41

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – MOS (Mosqueiro)

→ stress-strain behavior; sample 743/MOS017/TC_d6

Appendix 42

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	**4**						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Overview of planned tests

Unit – Marituba (Marituba II)

Appendix 43

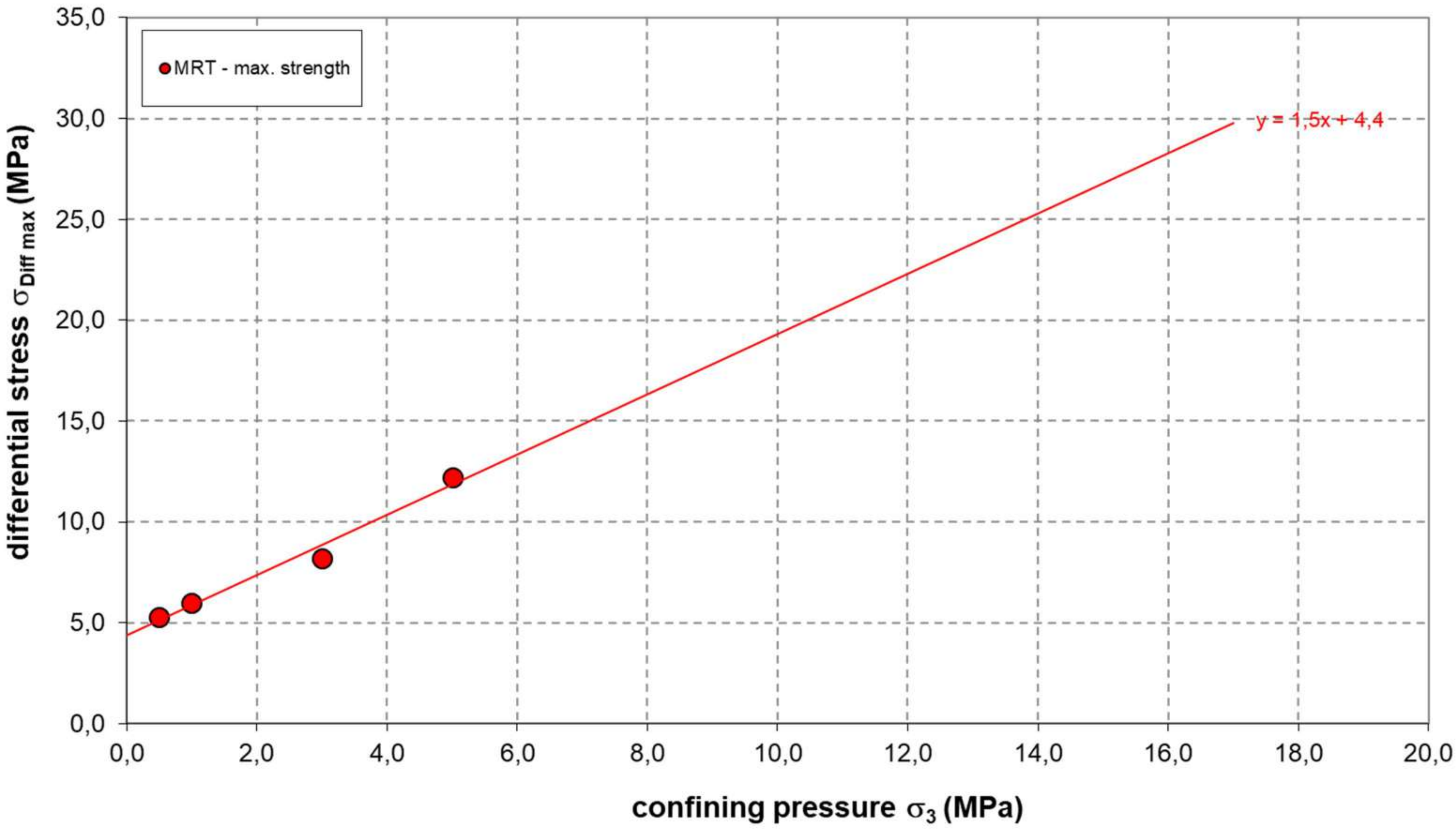
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

IfG - Lab-No.	743/MRT005/TC_d1	743/MRT006/TC_d2	743/MRT007/TC_d3	743/MRT008/TC_d4
Rock Type / Unit	MRT	MRT	MRT	MRT
Sample	MRT_005	MRT_006	MRT_007	MRT_008
Depth (m)				
Length l (mm) =	188.060	198.568	189.383	185.910
Diameter d (mm) =	99.393	99.892	99.157	99.442
Ratio l_o/d_o =	1.89	1.99	1.91	1.87
Mass M (g) =	3286.60	3413.5	3070.5	2981.2
Area A (cm^2) =	77.589	78.370	77.221	77.666
Volume V (cm^3) =	1459.14	1556.18	1462.44	1443.88
Density ρ (g/cm^3) =	2.252	2.194	2.100	2.065
US L (h) - p	-	-	-	-
US Q1 (a/c) - p	-	-	-	-
US Q2 (b/d) - p	-	-	-	-
US L (h) - s	-	-	-	-
US L (h) - p(s)	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-
E_d (GPa) =	-	-	-	-
K_d (GPa) =	-	-	-	-
G_d (GPa) =	-	-	-	-
ν_d =	-	-	-	-
	TC	TC	TC	TC
Temp. (°C)	23	23	23	23
σ_3 (MPa) =	0.5	1.0	3.0	5.0
σ_{Dil} (MPa) =	4.1	4.6	8.0	12.0
ΔV_{Dil} (%) =	-0.27	-0.39	-0.53	-2.20
ε_{Dil} (%) =	0.59	0.92	2.54	12.90
σ_{Fail} (MPa) =	5.3	6.0	8.2	12.2
ΔV_{Fail} (%) =	0.15	0.06	-0.45	-2.19
ε_{Fail} (%) =	1.63	2.28	5.36	12.53
σ_{1Fail} (MPa) =	5.80	6.98	11.19	17.19
α (°) =	65	65	65	65
σ_n (MPa) =	1.45	2.07	4.46	7.18
τ (MPa) =	2.03	2.29	3.14	4.67
ϕ=	25.3			
C=	1.4			

BEFORE:

AFTER:

σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 3.0 MPa | σ_3 = 5.0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

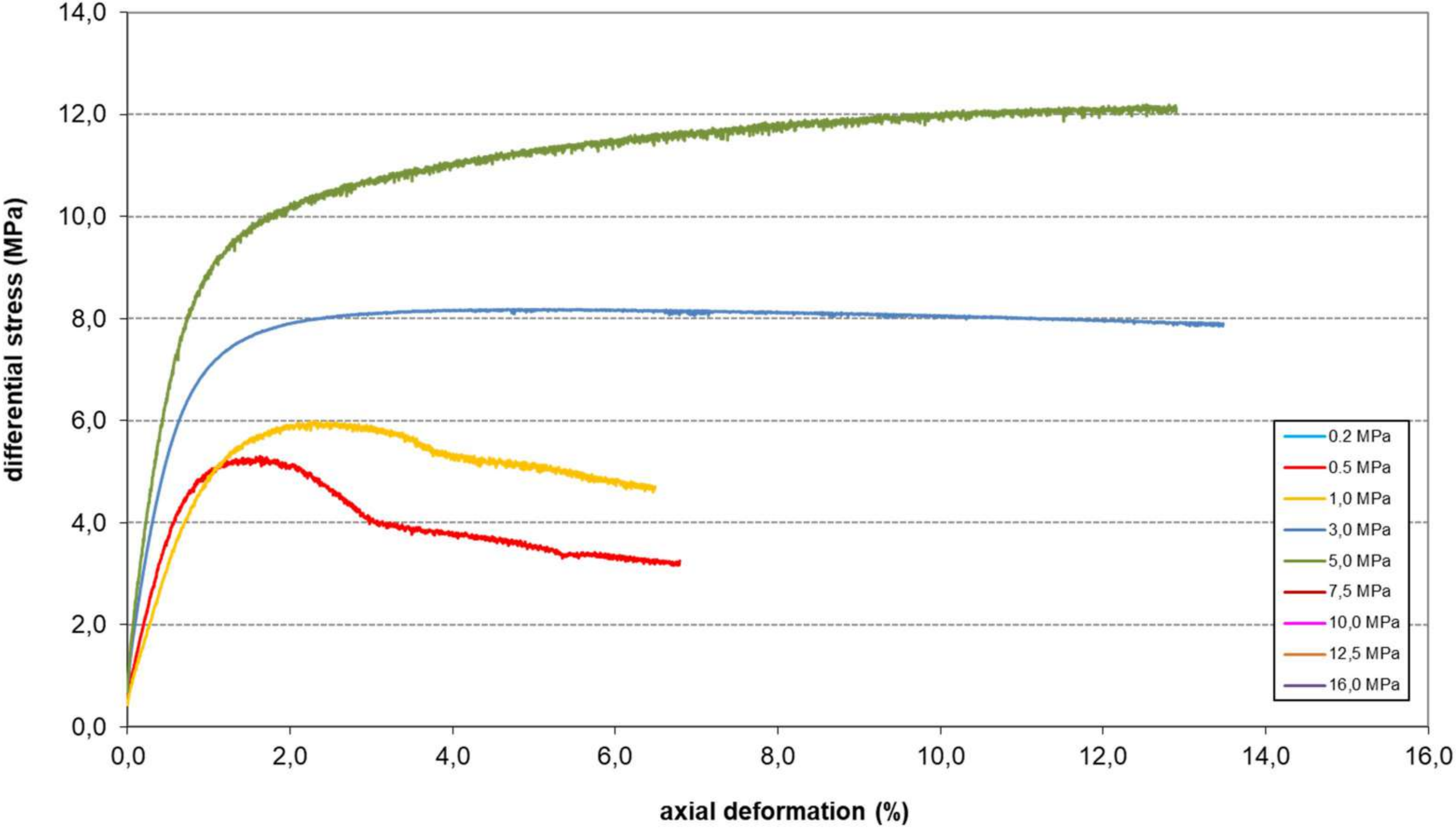
Triaxial strength tests (TC_nat)

Unit – MRT (Marituba II)

→ maximum strength values dependent on the radial stress

Appendix 46

B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”



INSTITUT FÜR GEBIRGSMECHANIK GMBH

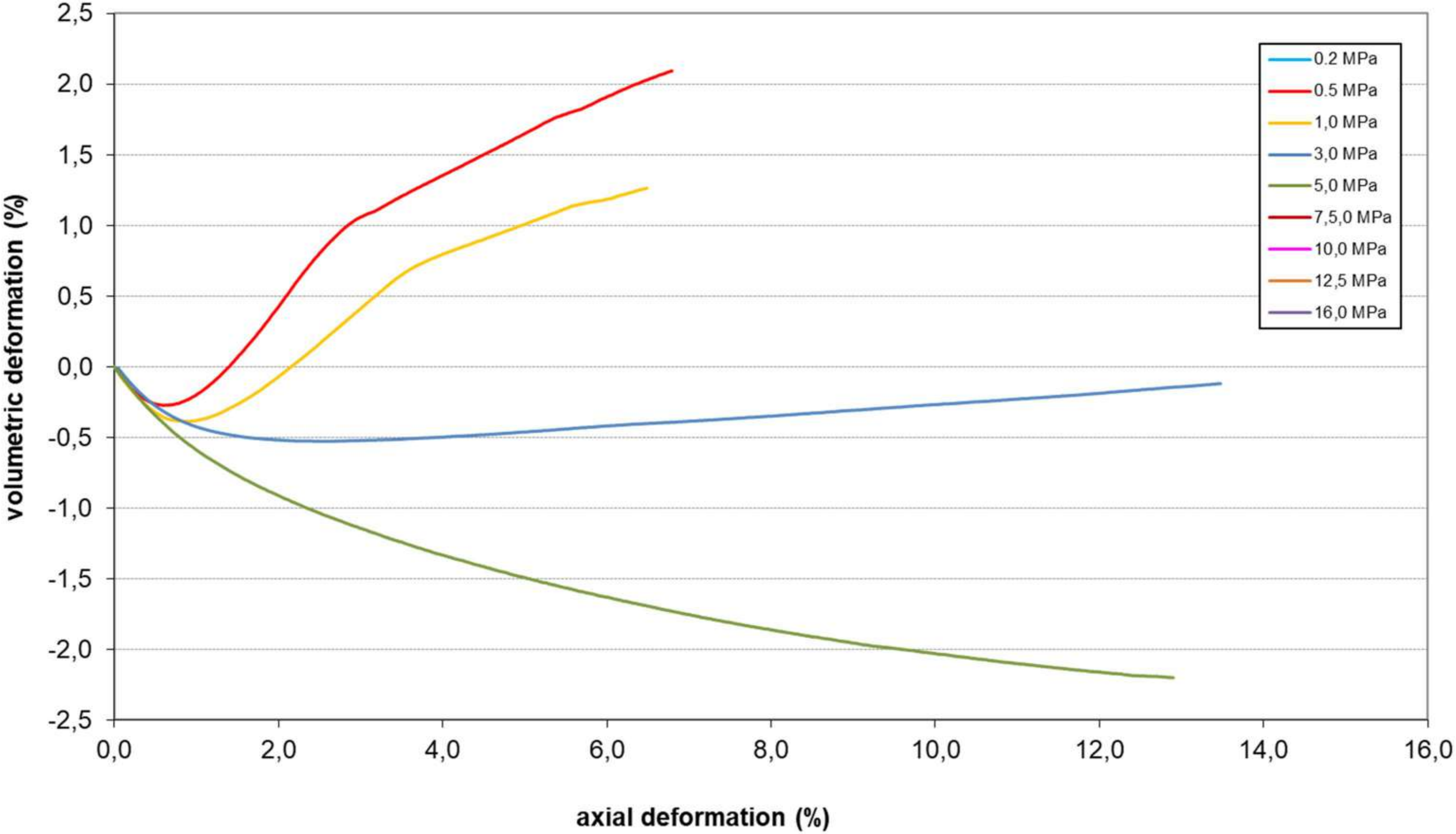
Triaxial strength tests (TC_nat)

Unit – MRT (Marituba II)

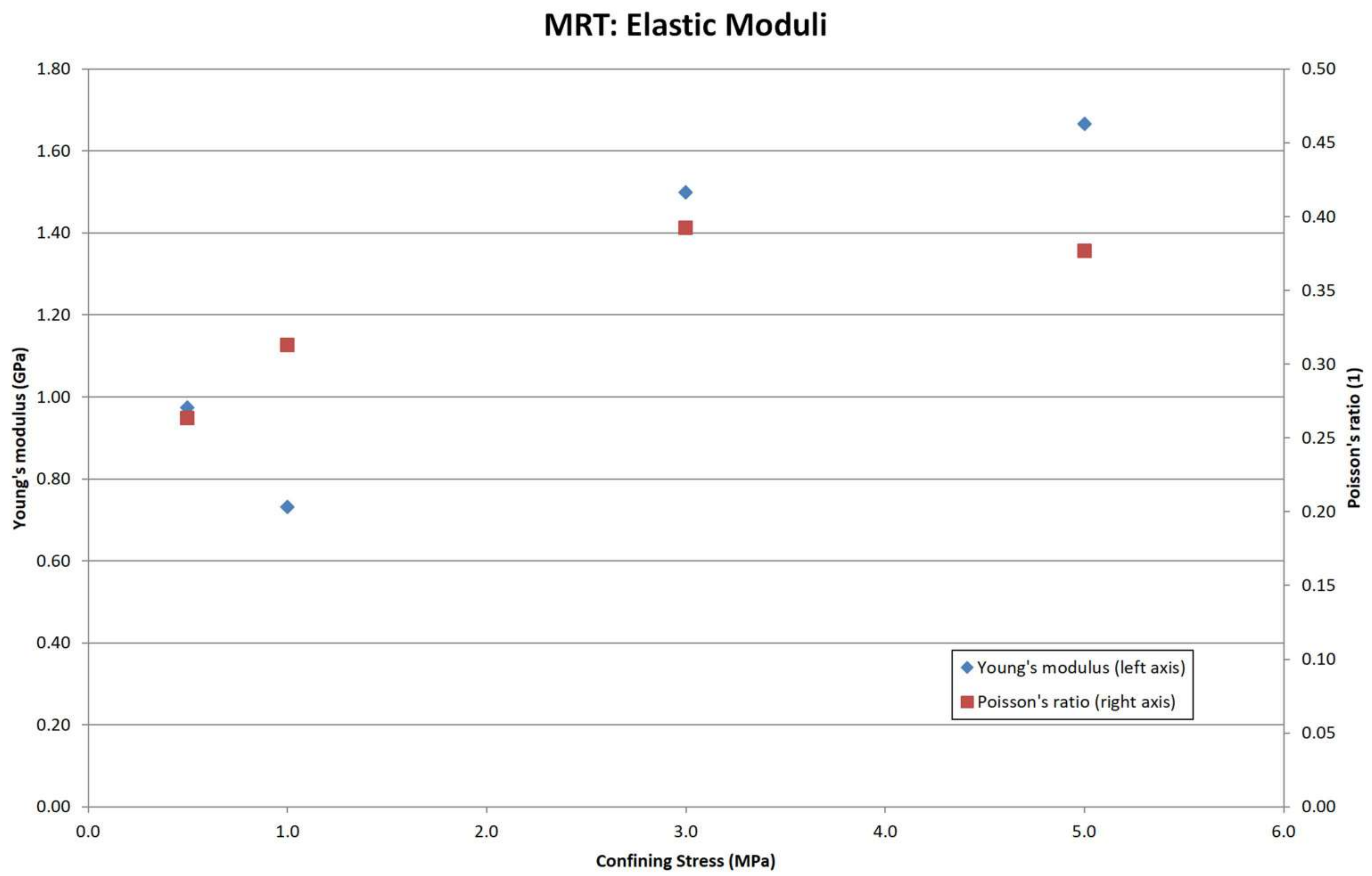
→ stress-strain curves of all tests

Appendix 47

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



2,5
2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
-2,5
volumetric deformation (%)
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
16,0
axial deformation (%)
0.2 MPa
0.5 MPa
1,0 MPa
3,0 MPa
5,0 MPa
7,5,0 MPa
10,0 MPa
12,5 MPa
16,0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

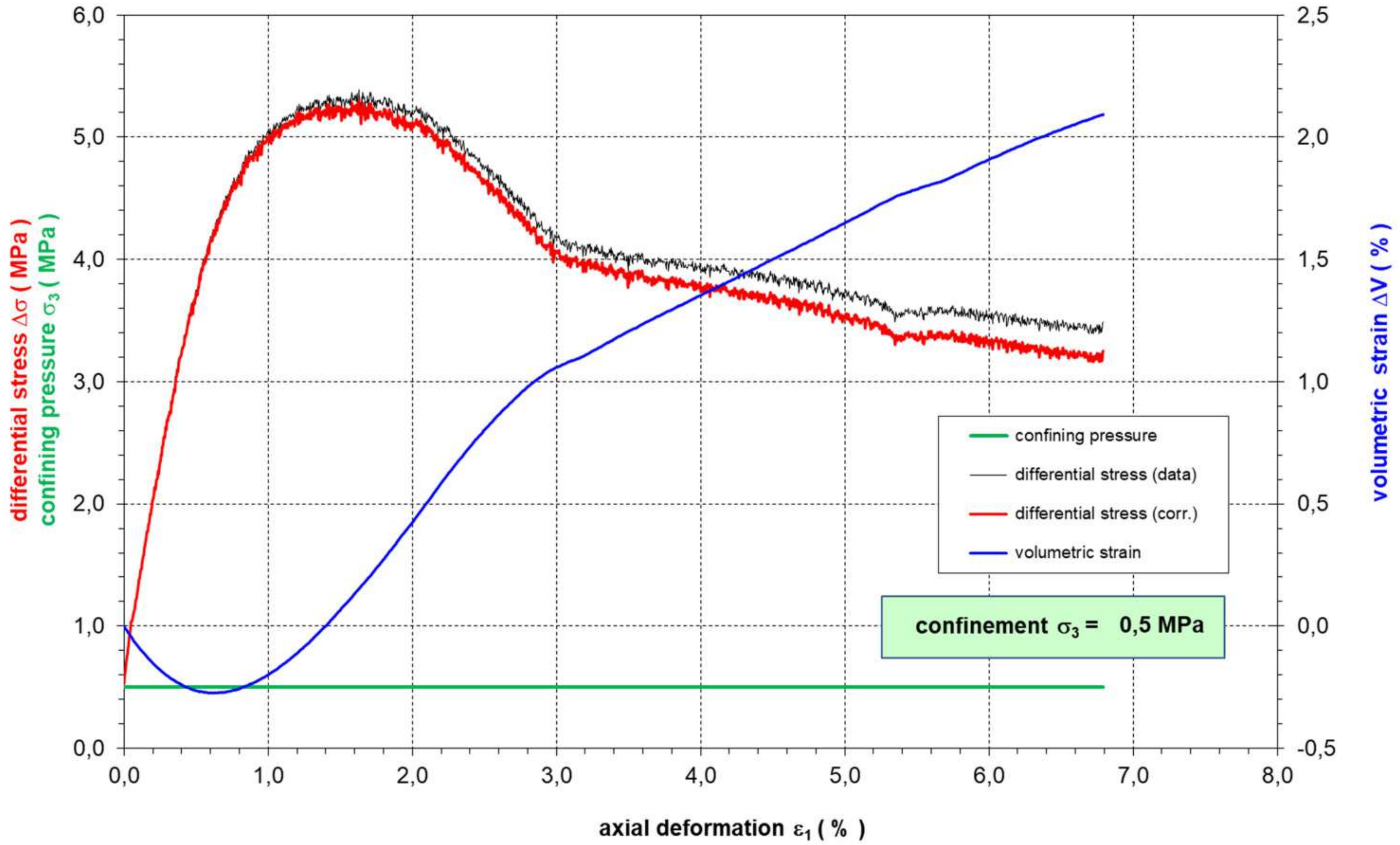
Triaxial strength tests (TC_nat)

Unit – MRT (Marituba II)

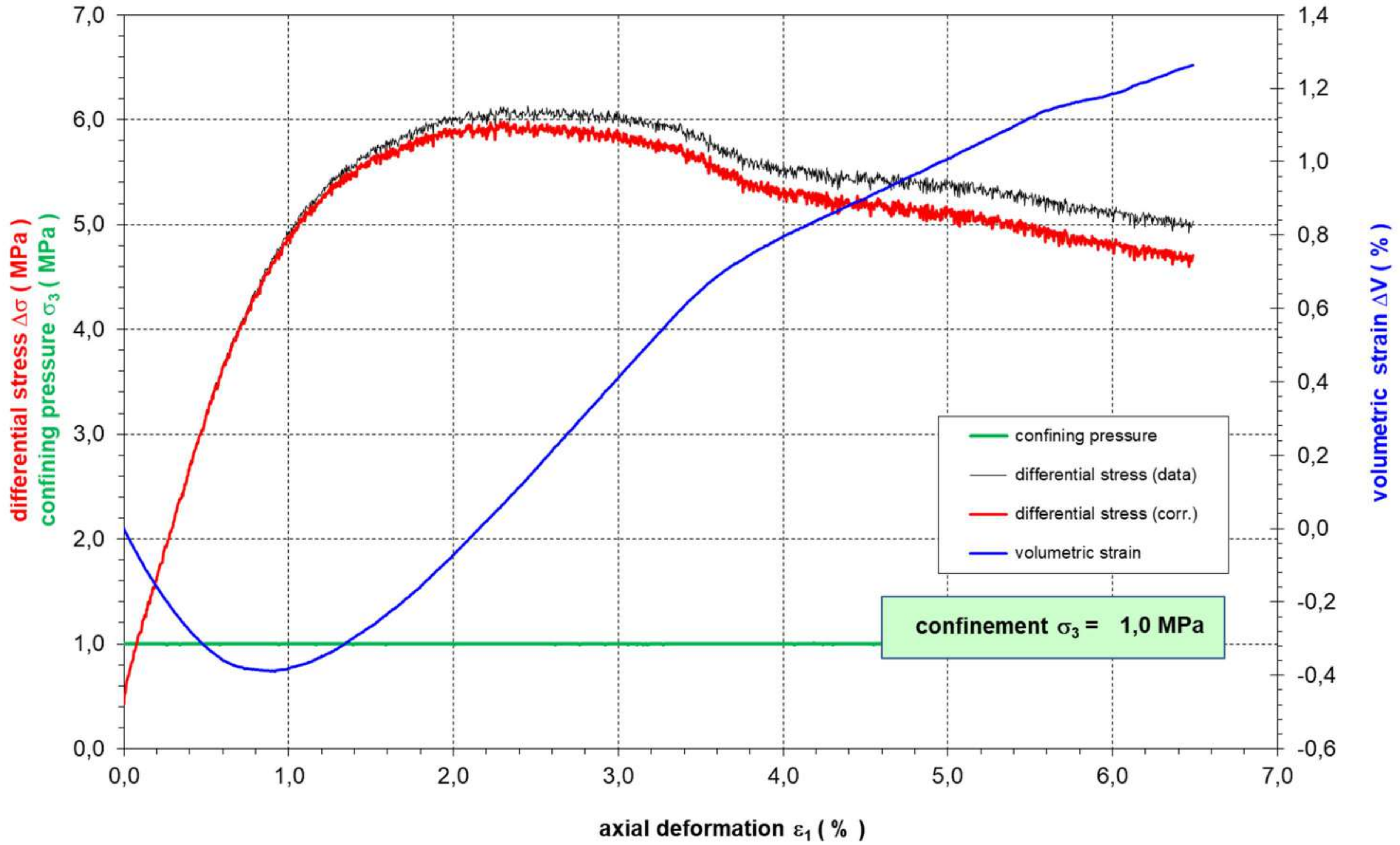
→ elastic parameters vs. confining stress

Appendix 49

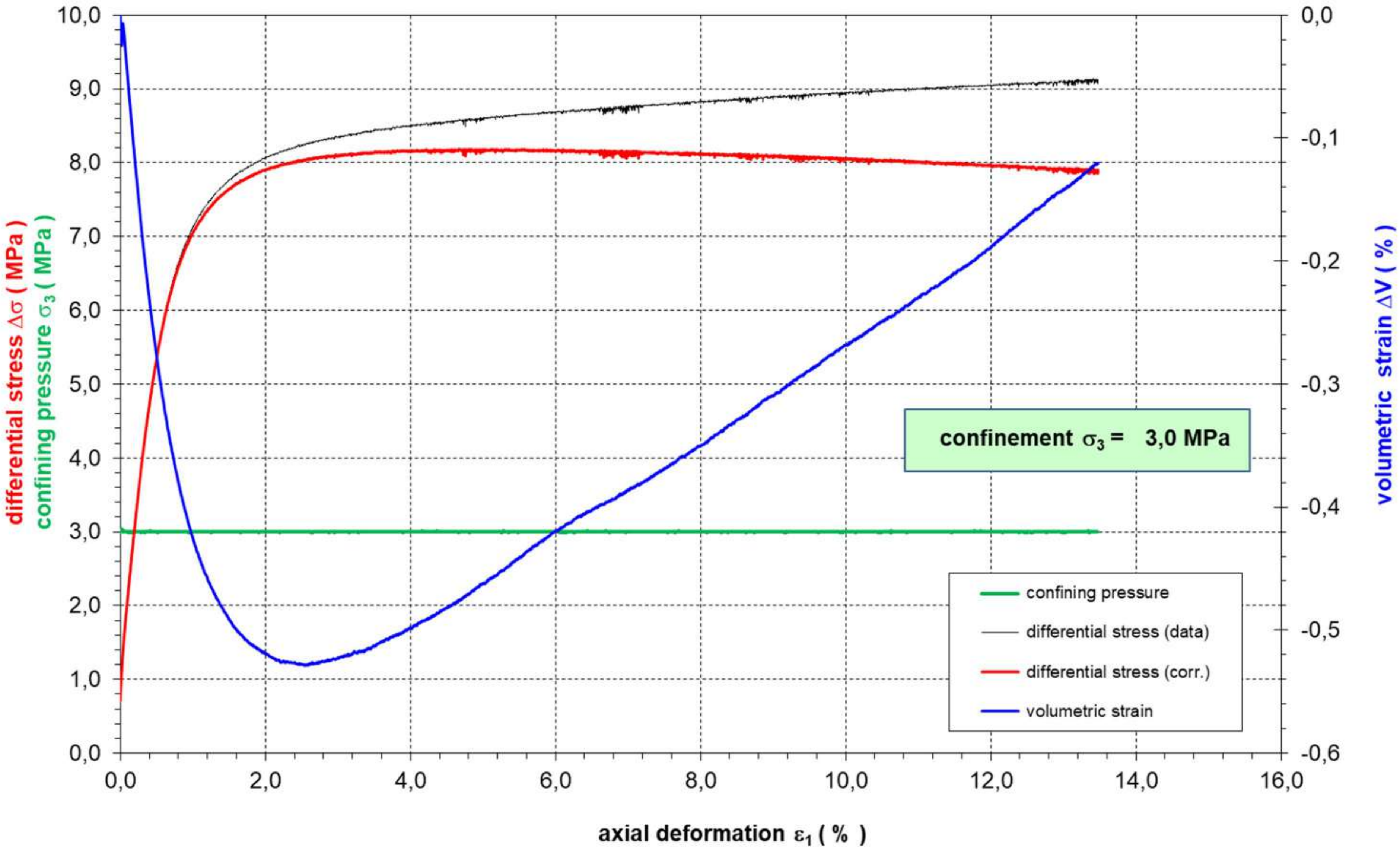
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



6,0
5,0
4,0
3,0
2,0
1,0
0,0
2,5
2,0
1,5
1,0
0,5
0,0
-0,5
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 0,5 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength test (TC_nat)** **Unit – MRT (Marituba II)** → stress-strain behavior; sample 743/MRT006/TC_d2	**Appendix 51** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



INSTITUT FÜR GEBIRGSMECHANIK GMBH

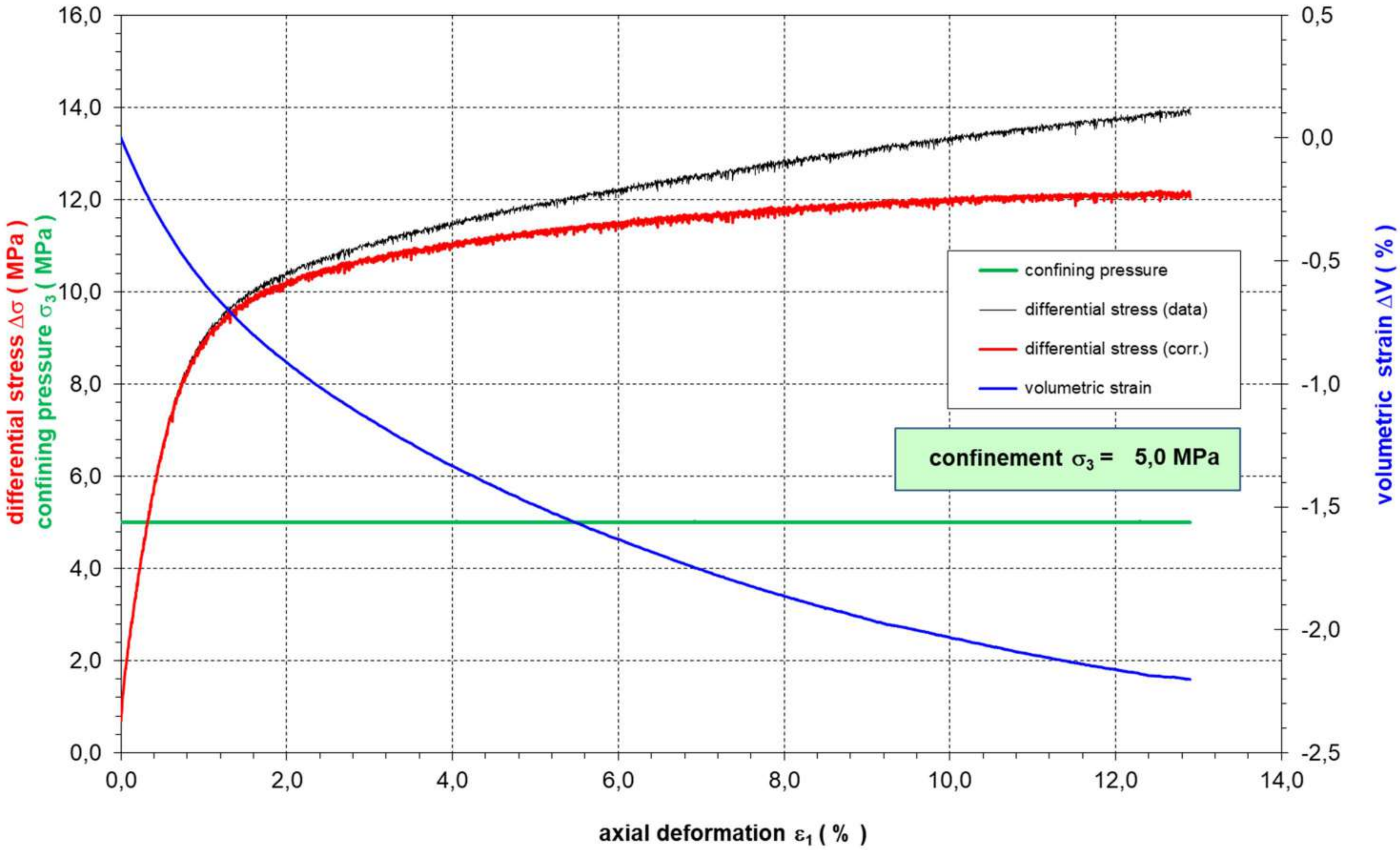
Triaxial strength test (TC_nat)

Unit – MRT (Marituba II)

→ stress-strain behavior; sample 743/MRT007/TC_d3

Appendix 52

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH	**Triaxial strength test (TC_nat)** **Unit – MRT (Marituba II)** → stress-strain behavior; sample 743/MRT008/TC_d4	**Appendix 53** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	**9**	**9**		**6**	**6**		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/IBU008/TC_d1	743/IBU008/TC_d2	743/IBU007/TC_d3	743/IBU009/TC_d4
Rock Type / Unit	IBU	IBU	IBU	IBU
Sample	IBU_008	IBU_008	IBU_007	IBU_009
Depth (m)				
Length l (mm) =	199.930	190.722	198.635	199.668
Diameter d (mm) =	100.695	100.745	100.642	100.583
Ratio l_o/d_o =	1.99	1.89	1.97	1.99
Mass M (g) =	3436.90	3454.1	3645.9	3335.9
Area A (cm^2) =	79.635	79.714	79.552	79.458
Volume V (cm^3) =	1592.15	1520.33	1580.17	1586.53
Density ρ (g/cm^3) =	2.159	2.272	2.307	2.103
US L (h) - p	-	-	-	-
US Q1 (a/c) - p	-	-	-	28.51
US Q2 (b/d) - p	-	-	-	28.33
US L (h) - s	-	-	-	-
US L (h) - p(s)	-	-	-	
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	3.53
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	3.55
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-
E_d (GPa) =	-	-	-	-
K_d (GPa) =	-	-	-	-
G_d (GPa) =	-	-	-	-
ν_d =	-	-	-	-
	TC	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.5	1.0	3.0	5.0
σ_{Dil} (MPa) =	23.8	22.5	21.0	21.8
ΔV_{Dil} (%) =	-0.47	-0.33	-0.44	-1.88
ε_{Dil} (%) =	0.74	0.56	0.78	6.76
σ_{Fail} (MPa) =	24.9	22.6	22.0	23.6
ΔV_{Fail} (%) =	-0.45	-0.33	-0.43	-0.26
ε_{Fail} (%) =	0.85	0.56	0.68	0.38
σ_{1Fail} (MPa) =	25.43	23.56	24.98	28.57
α (°) =	65	65	65	65
σ_n (MPa) =	4.95	5.03	6.93	9.21
τ (MPa) =	9.55	8.64	8.42	9.03
ϕ=	**-5.3**			
C=	**13.0**			

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

Unit – IBU (Ibura)

→ petrophysical parameters and stress-strain-values

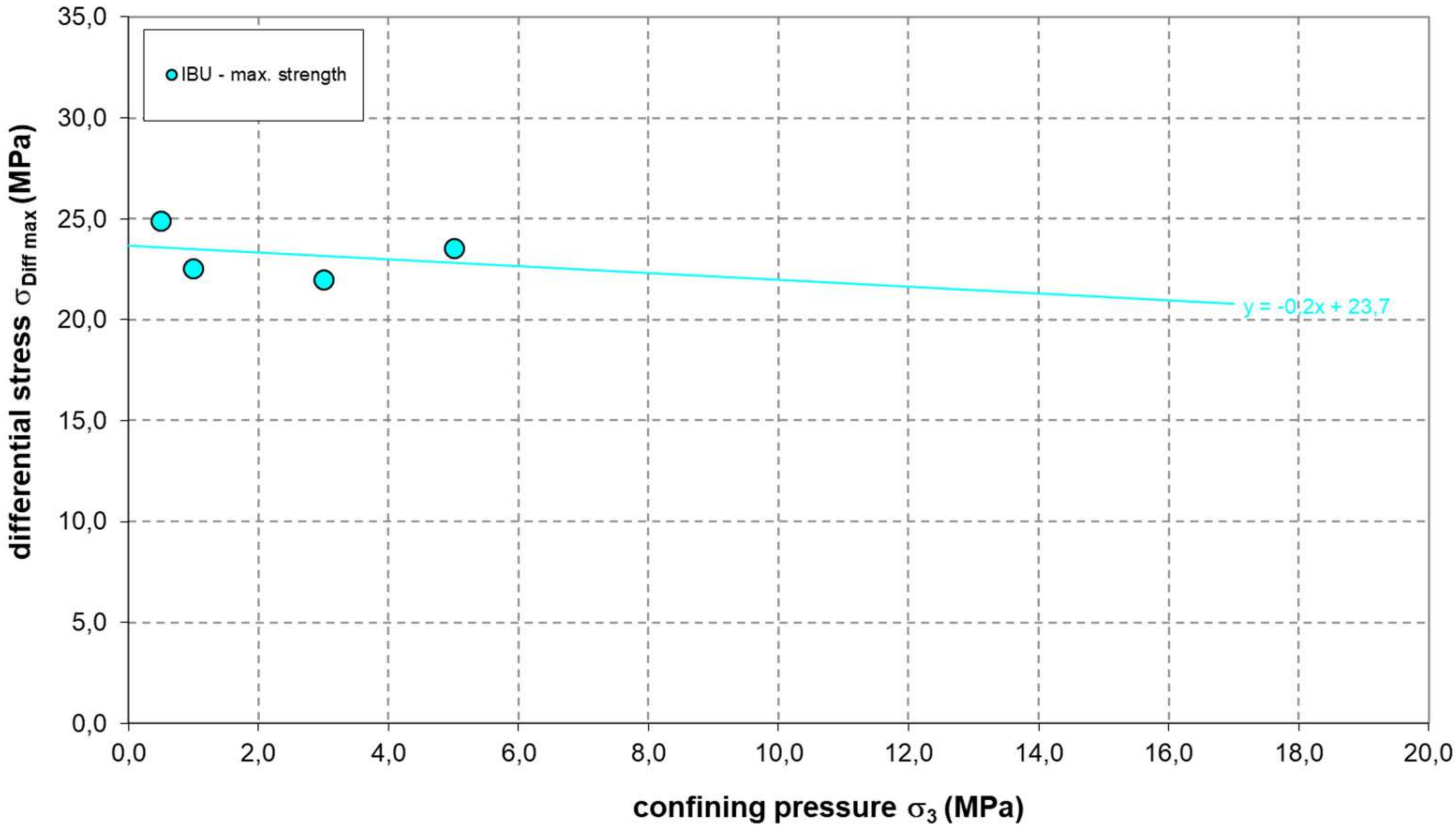
Appendix 55

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:

AFTER:

σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 3.0 MPa | σ_3 = 5.0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

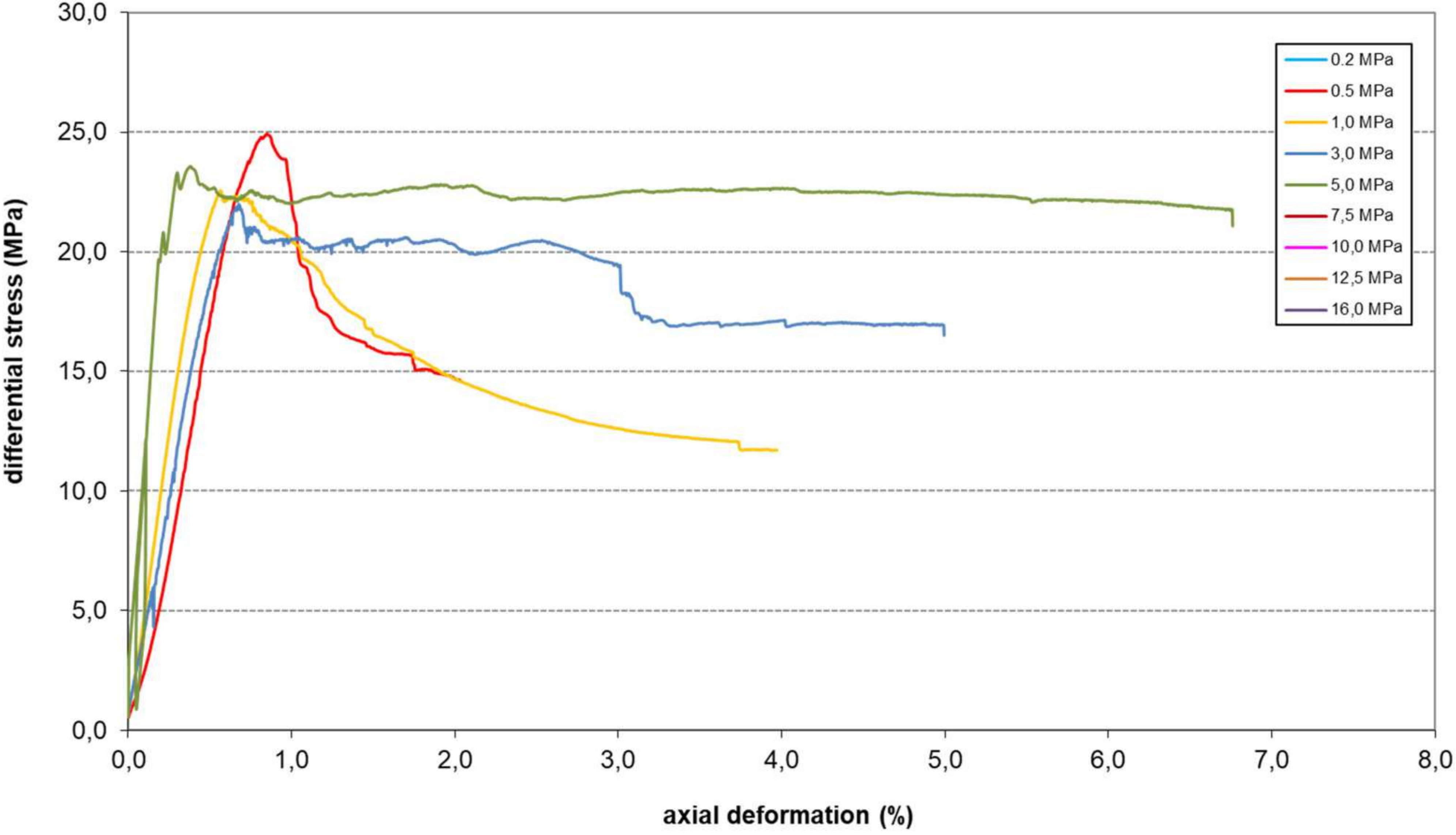
Triaxial strength tests (TC_nat)

Unit – IBU (Ibura)

→ maximum strength values dependent on the radial stress

Appendix 57

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

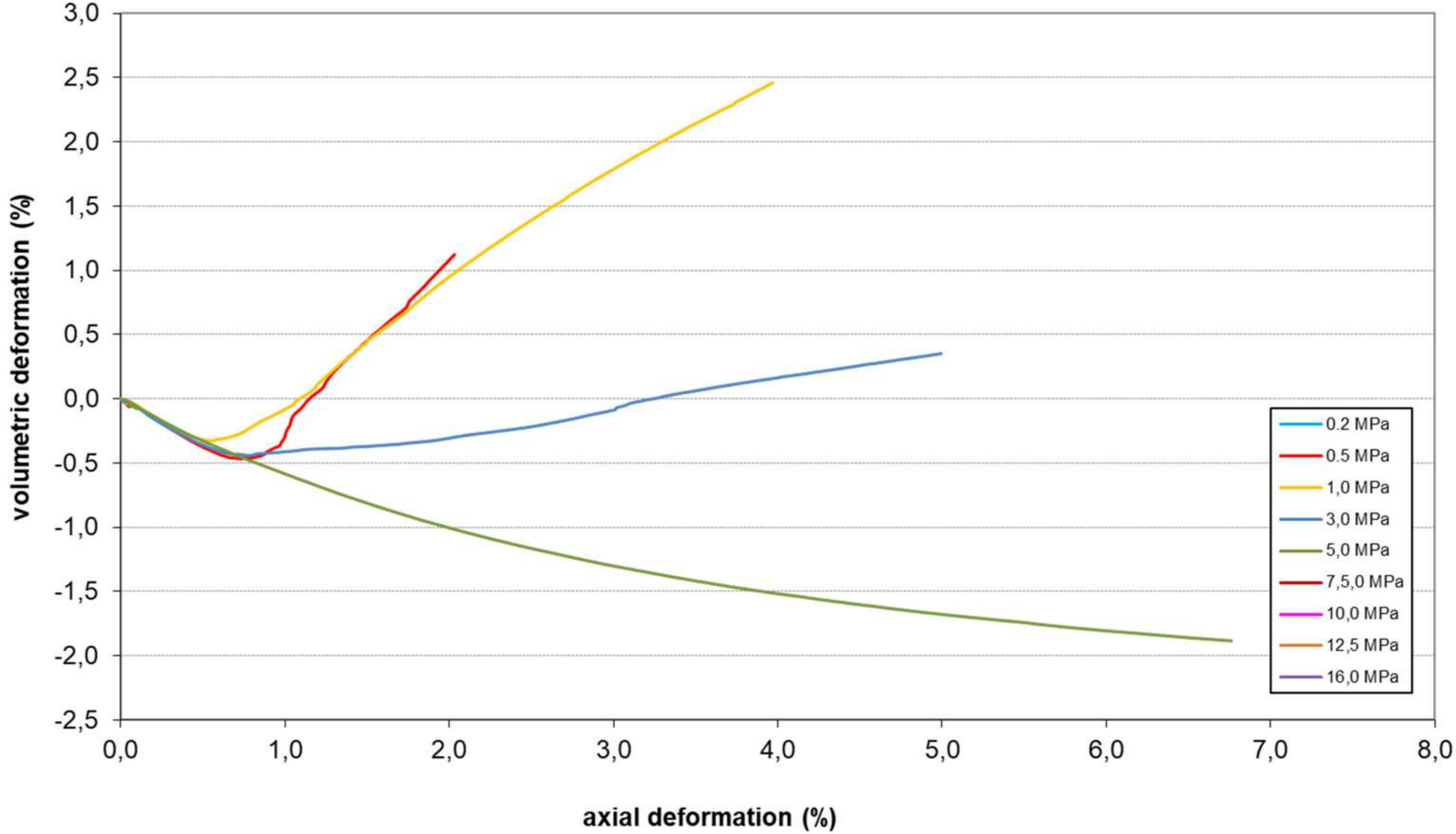
Triaxial strength tests (TC_nat)

Unit – IBU (Ibura)

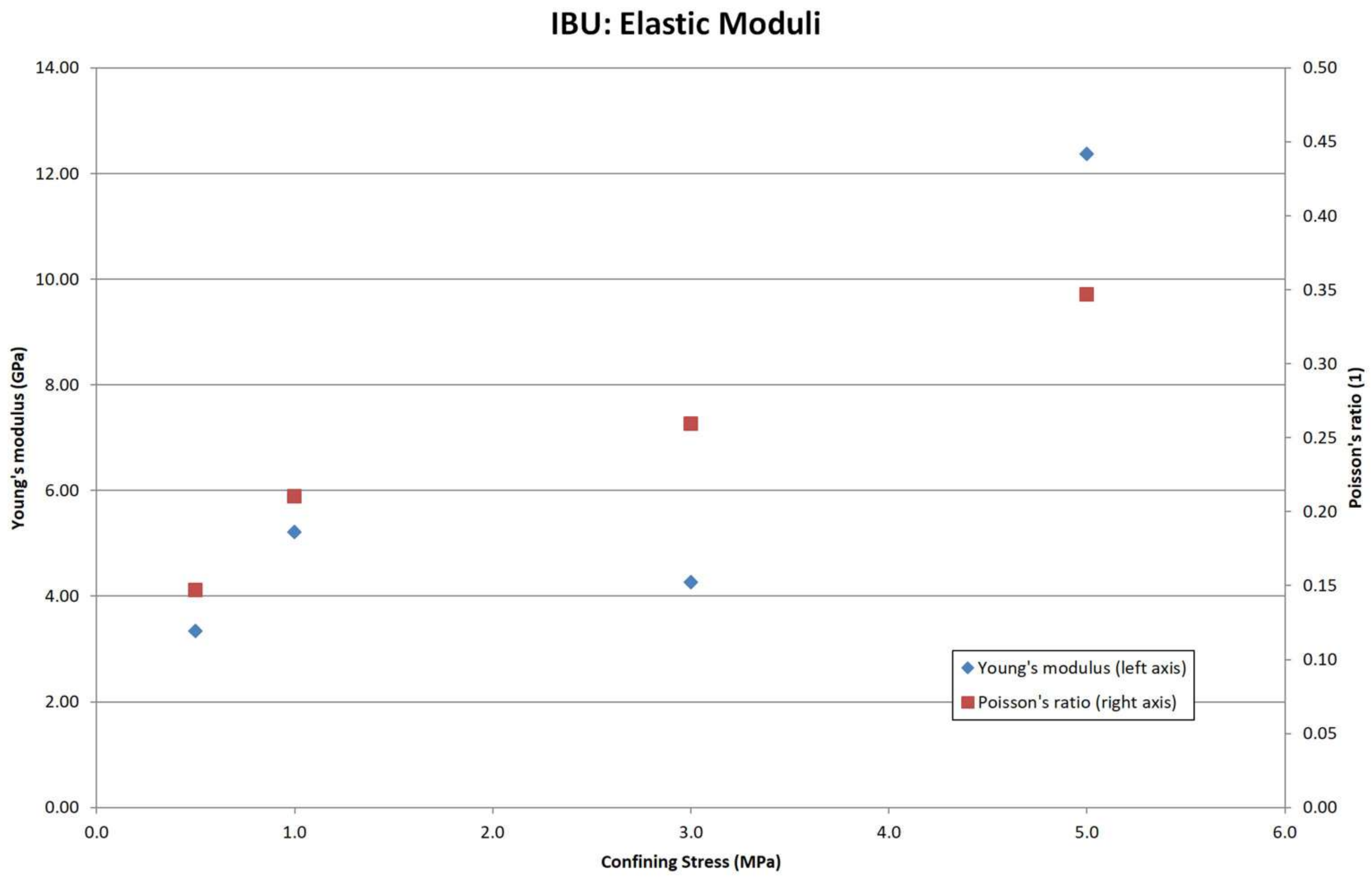
→ stress-strain curves of all tests

Appendix 58

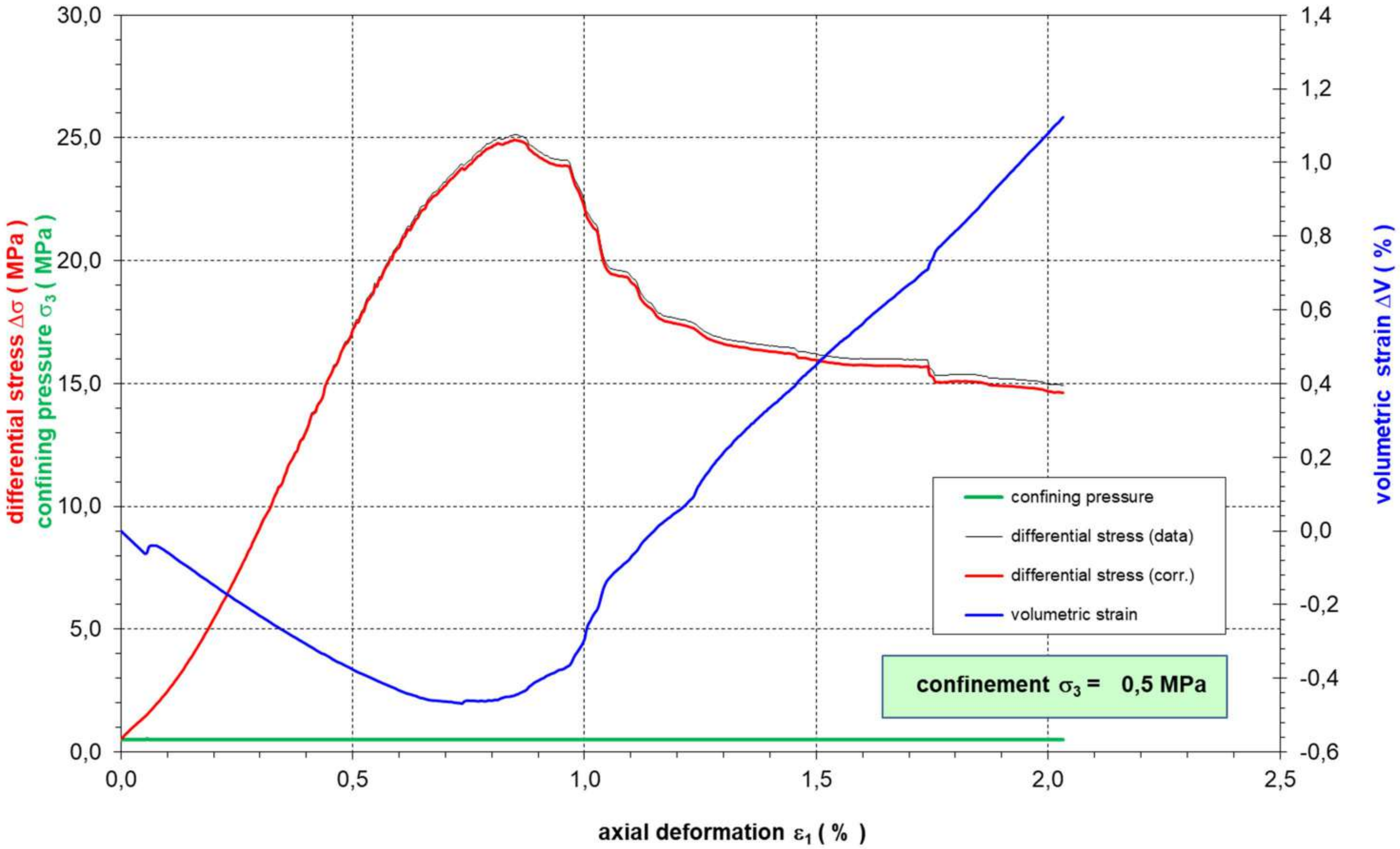
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH	**Triaxial strength tests (TC_nat)** **Unit – IBU (Ibura)** → volumetric strain vs. axial deformation; dilatancy curves	**Appendix 59** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



IBU: Elastic Moduli
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Young's modulus (GPa)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Poisson's ratio (1)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Confining Stress (MPa)
Young's modulus (left axis)
Poisson's ratio (right axis)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

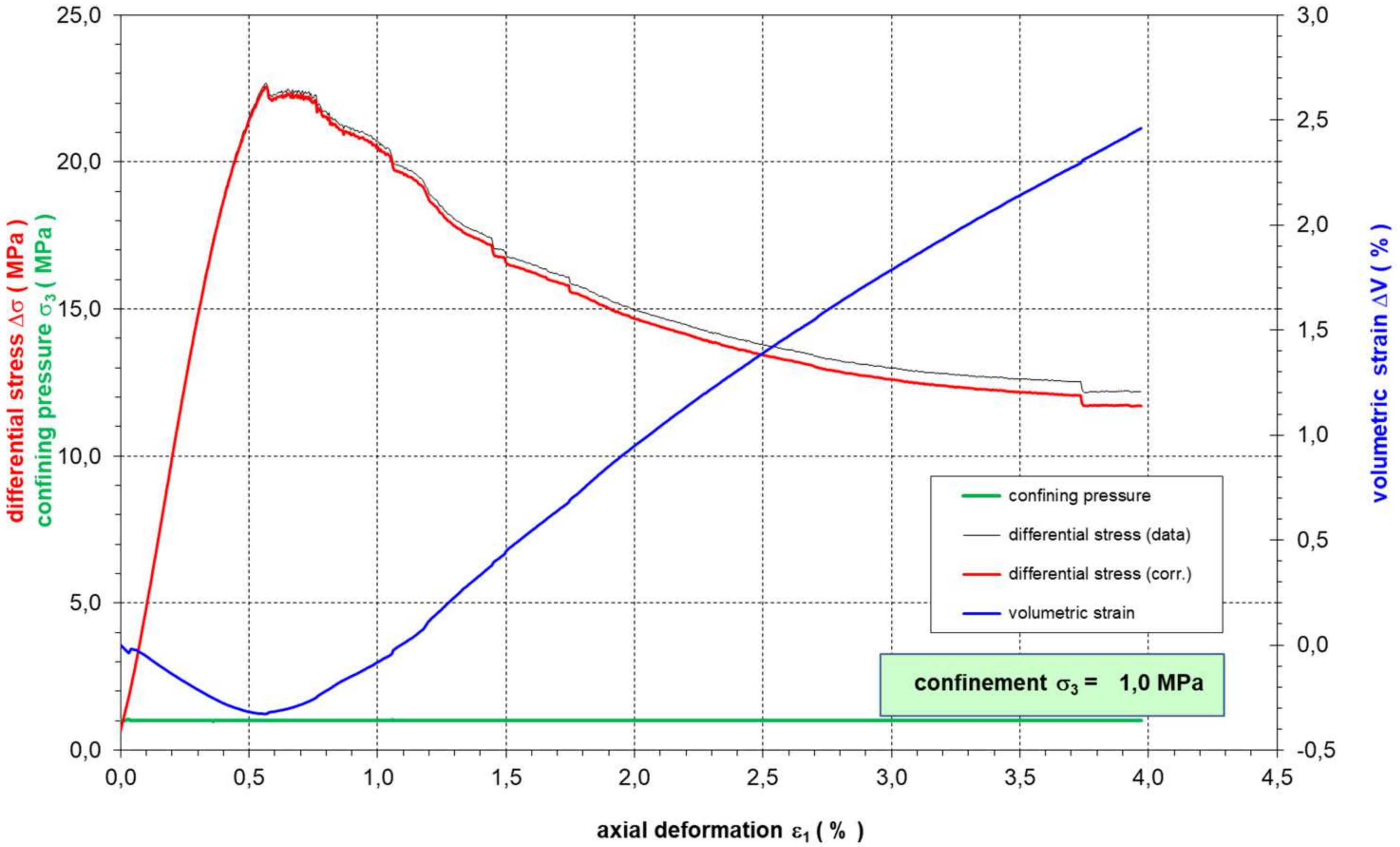
Triaxial strength test (TC_nat)

Unit – IBU (Ibura)

→ stress-strain behavior; sample 743/IBU008/TC_d1

Appendix 61

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

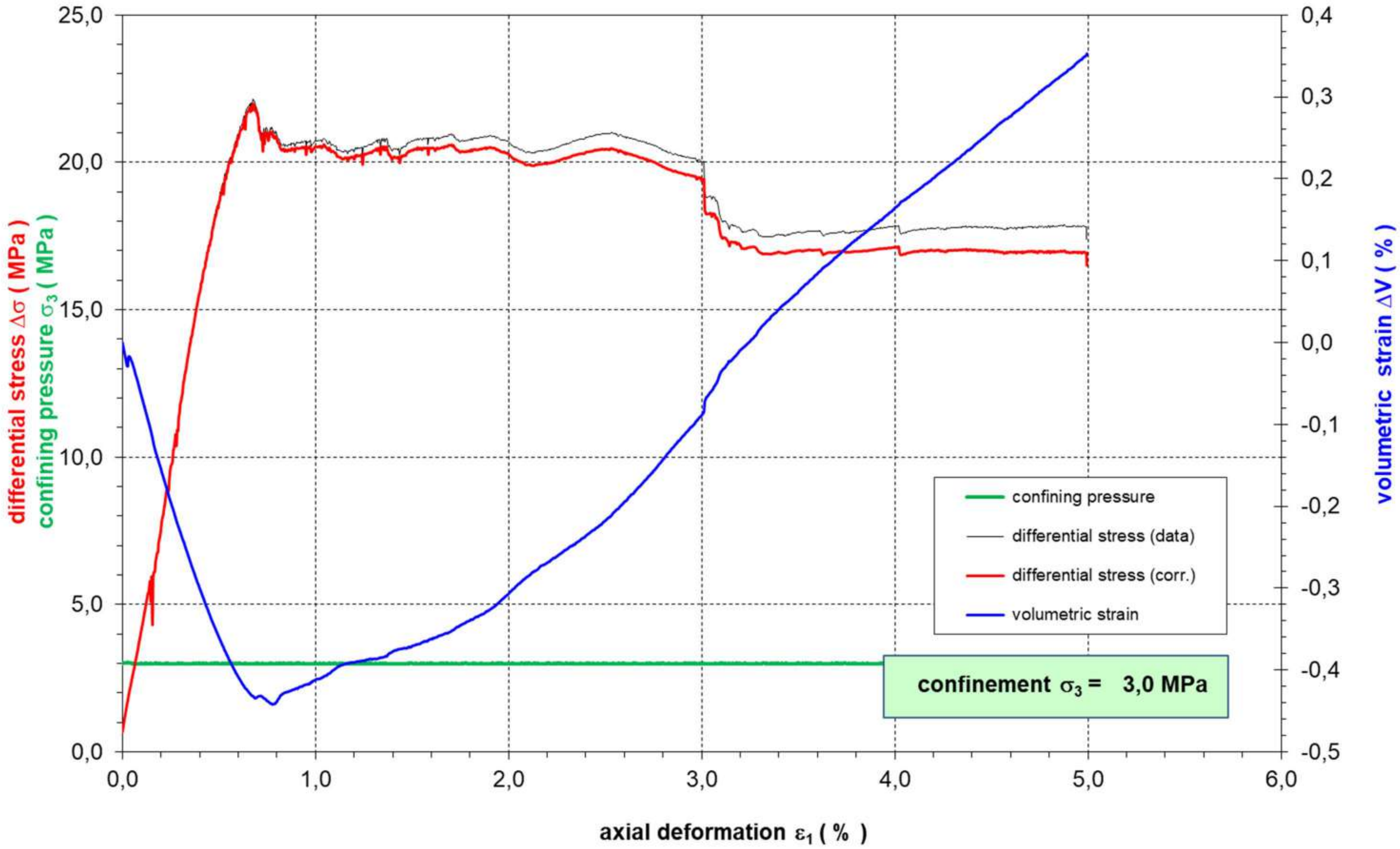
Triaxial strength test (TC_nat)

Unit – IBU (Ibura)

→ stress-strain behavior; sample 743/IBU008/TC_d2

Appendix 62

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

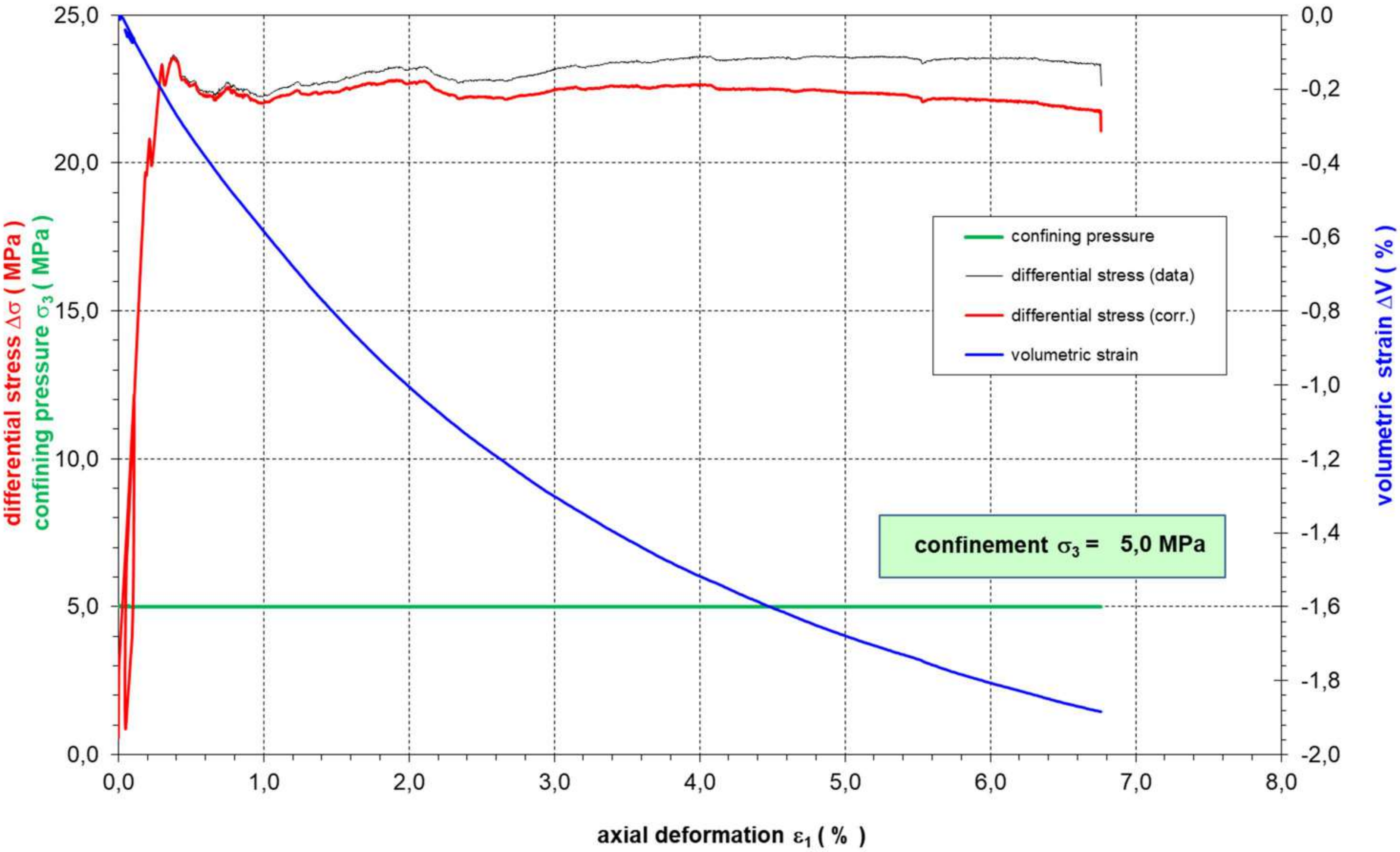
Triaxial strength test (TC_nat)

Unit – IBU (Ibura)

→ stress-strain behavior; sample 743/IBU007/TC_d3

Appendix 63

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



IfG INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – IBU (Ibura)

→ stress-strain behavior; sample 743/IBU009/TC_d4

Appendix 64

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	**9**	**9**		**6**	**6**	**3**	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/PAR073/TC_d1	743/PAR072/TC_d2	743/PAR071/TC_d3	743/PAR067/TC_d6	743/PAR079/TC_d7
Rock Type / Unit	PAR	PAR	PAR	PAR	PAR
Sample	PAR_073	PAR_072	PAR_071	PAR_067	PAR_079
Depth (m)					
Length l (mm) =	192.913	198.878	197.470	197.670	199.305
Diameter d (mm) =	100.920	100.925	100.973	100.910	100.855
Ratio l_o/d_o =	1.91	1.97	1.96	1.96	1.98
Mass M (g) =	3017.60	3069.9	3030.7	3079.7	3028.5
Area A (cm^2) =	79.992	80.000	80.076	79.976	79.889
Volume V (cm^3) =	1543.14	1591.01	1581.25	1580.88	1592.22
Density ρ (g/cm^3) =	1.955	1.930	1.917	1.948	1.902
US L (h) - p	-	-	-	-	-
US Q1 (a/c) - p	-	-	-	-	-
US Q2 (b/d) - p	-	-	-	-	-
US L (h) - s	-	-	-	-	-
US L (h) - p(s)	-	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-
E_d (GPa) =	-	-	-	-	-
K_d (GPa) =	-	-	-	-	-
G_d (GPa) =	-	-	-	-	-
ν_d =	-	-	-	-	-
	TC	**TC**	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.5	1.0	2.0	5.0	10.0
σ_{Dil} (MPa) =	6.0	7.0	9.8	13.4	18.4
ΔV_{Dil} (%) =	-0.55	-0.64	-0.75	-1.62	-4.78
ε_{Dil} (%) =	0.92	1.05	1.36	9.10	9.05
σ_{Fail} (MPa) =	6.8	7.5	10.3	15.8	18.4
ΔV_{Fail} (%) =	-0.45	-0.58	-0.74	-0.70	-4.78
ε_{Fail} (%) =	1.15	1.25	1.52	1.33	9.04
σ_{1Fail} (MPa) =	7.30	8.49	12.26	20.77	28.37
α (°) =	65	65	65	65	65
σ_n (MPa) =	1.71	2.34	3.83	7.82	13.28
τ (MPa) =	2.60	2.87	3.93	6.04	7.04
ϕ=			**22.5**		
C=			**2.4**		

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

Unit – PAR (Poção Arenito)

→ petrophysical parameters and stress-strain-values

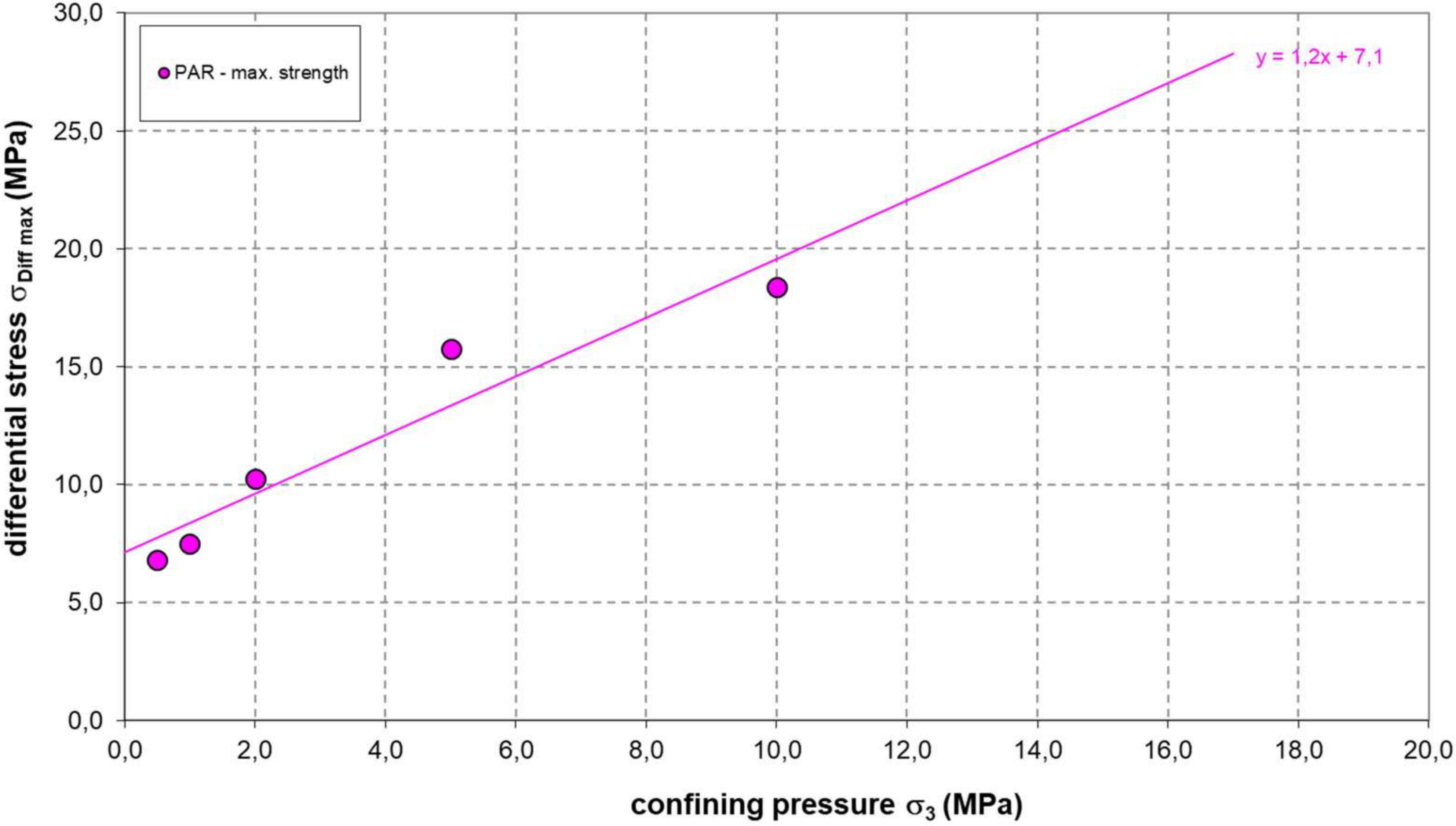
Appendix 66

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:

AFTER:

σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 2.0 MPa | σ_3 = 5.0 MPa | σ_3 = 10.0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

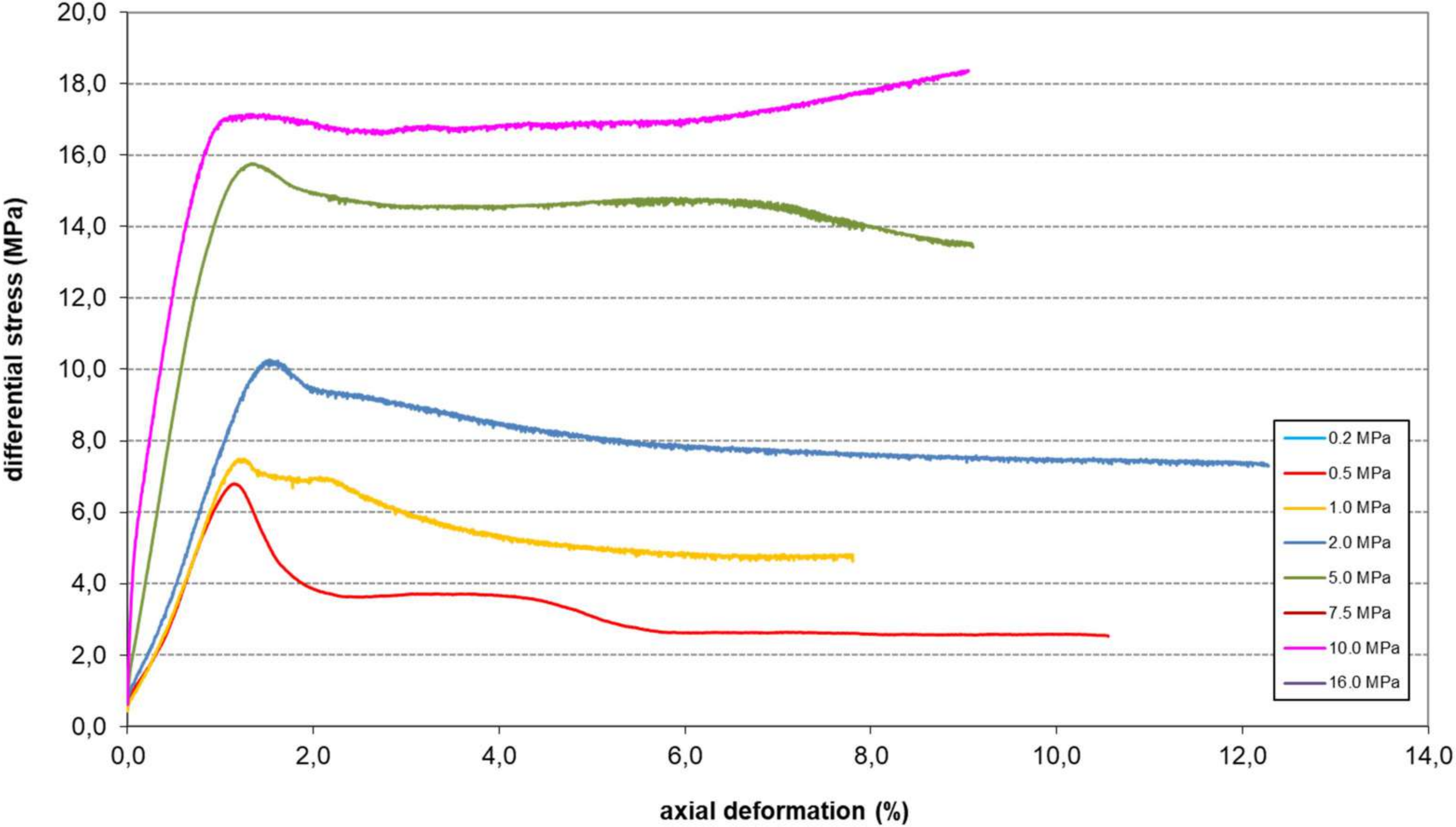
Triaxial strength tests (TC_nat)

Unit – PAR (Poção Arenito)

→ maximum strength values dependent on the radial stress

Appendix 68

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

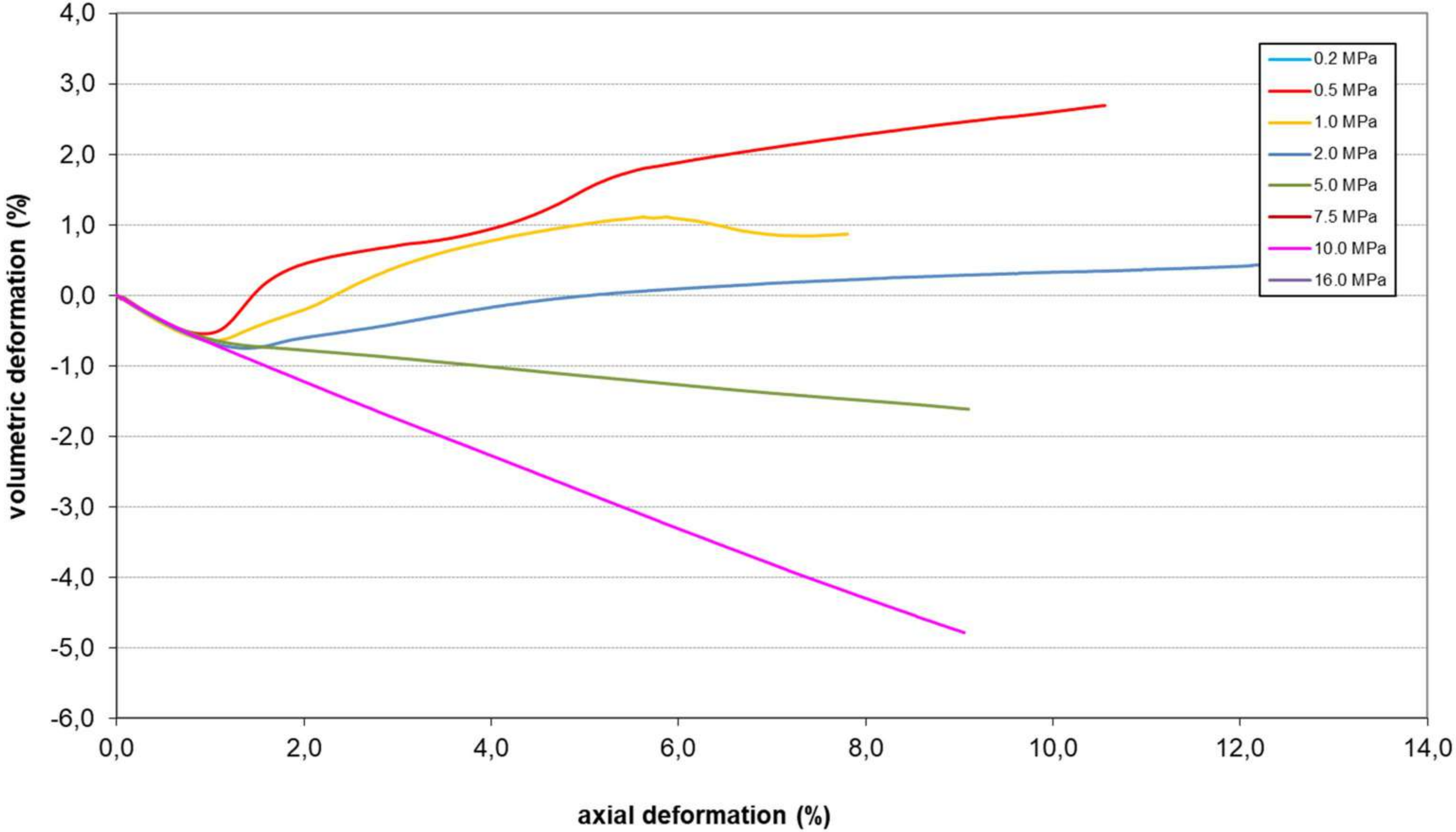
Triaxial strength tests (TC_nat)

Unit – PAR (Poção Arenito)

→ stress-strain curves of all tests

Appendix 69

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

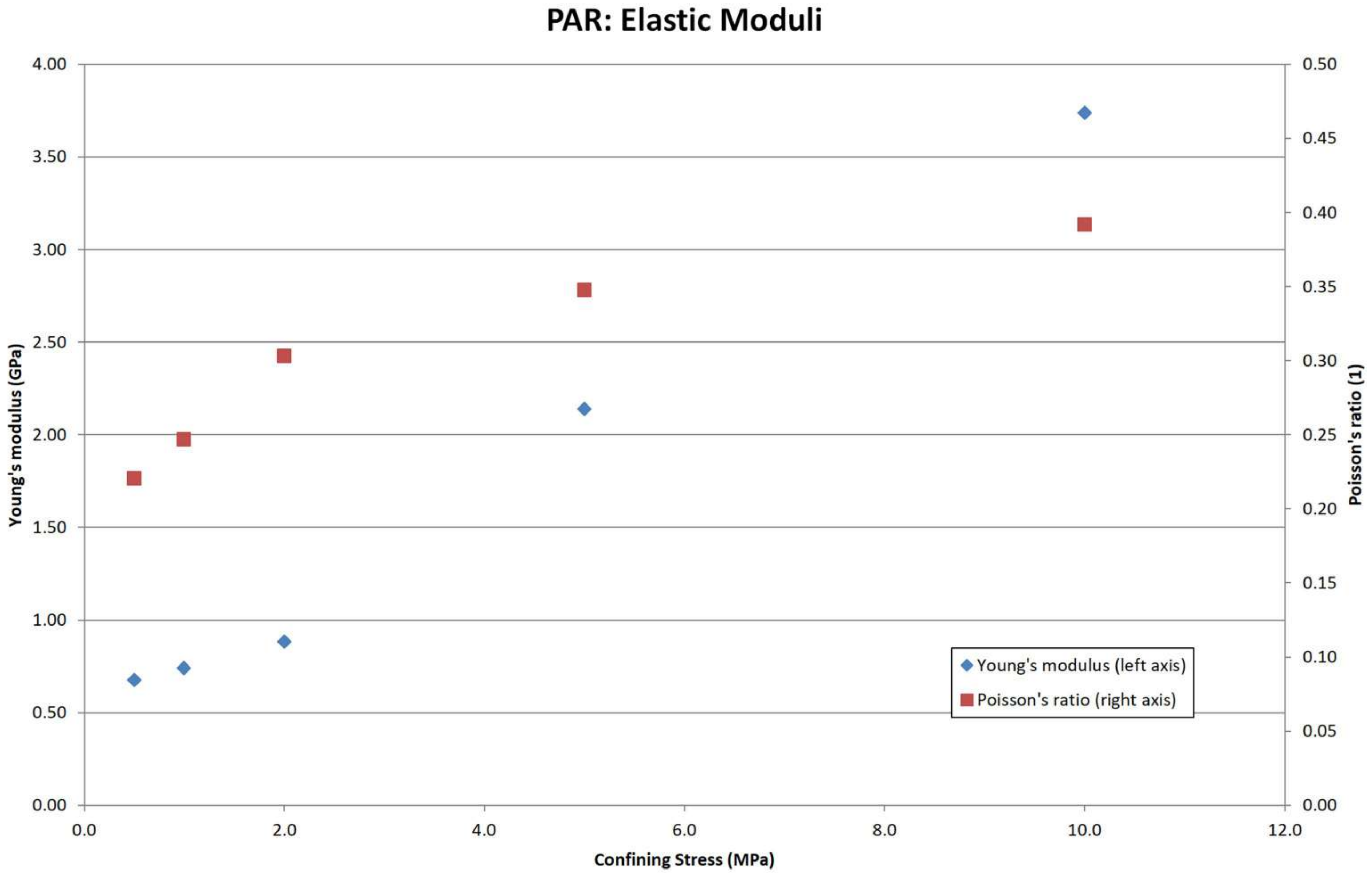
Triaxial strength tests (TC_nat)

Unit – PAR (Poção Arenito)

→ volumetric strain vs. axial deformation; dilatancy curves

Appendix 70

B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”



INSTITUT FÜR GEBIRGSMECHANIK GMBH

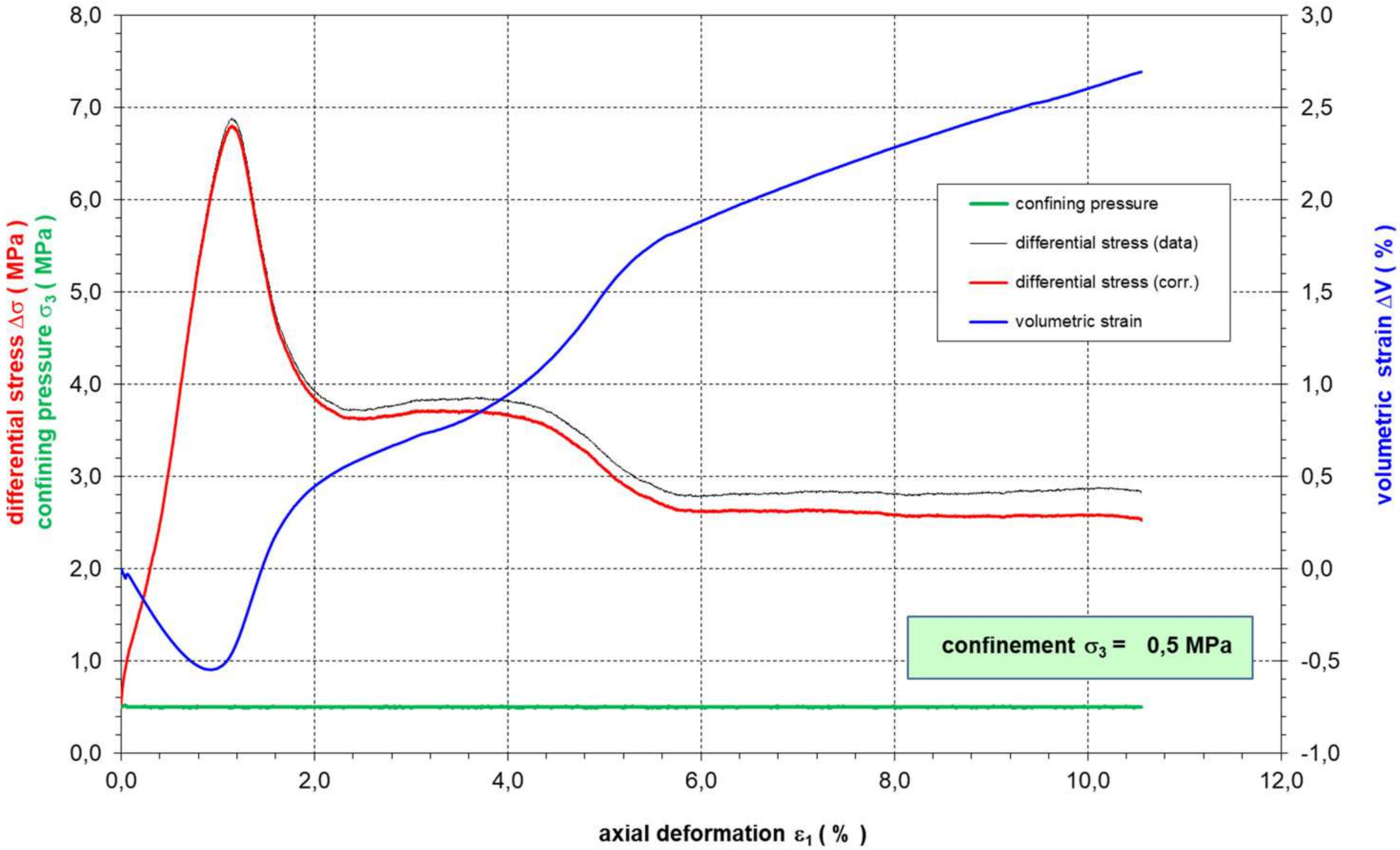
Triaxial strength tests (TC_nat)

Unit – PAR (Poção Arenito)

→ elastic parameters vs. confining stress

Appendix 71

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

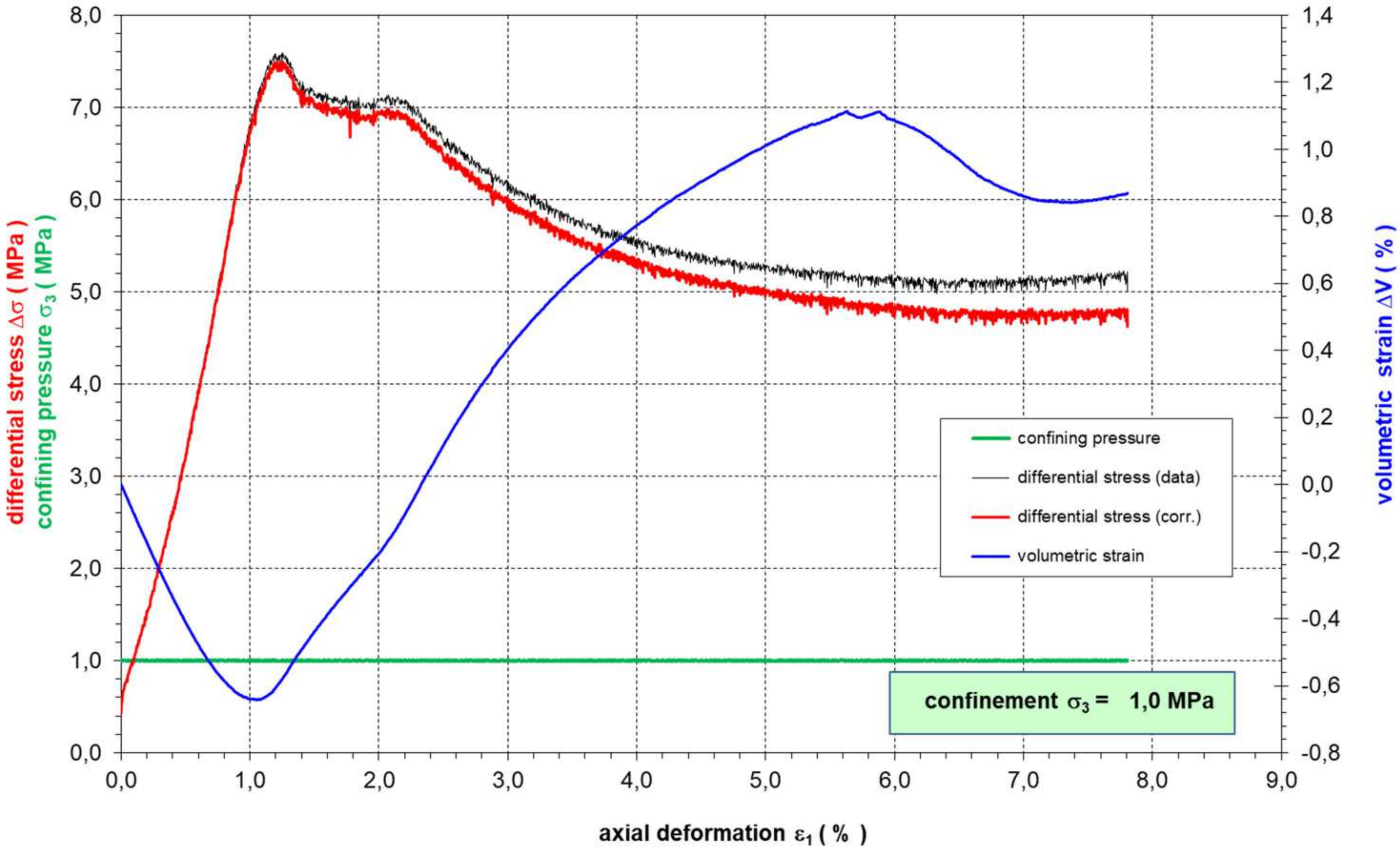
Triaxial strength test (TC_nat)

Unit – PAR (Poção Arenito)

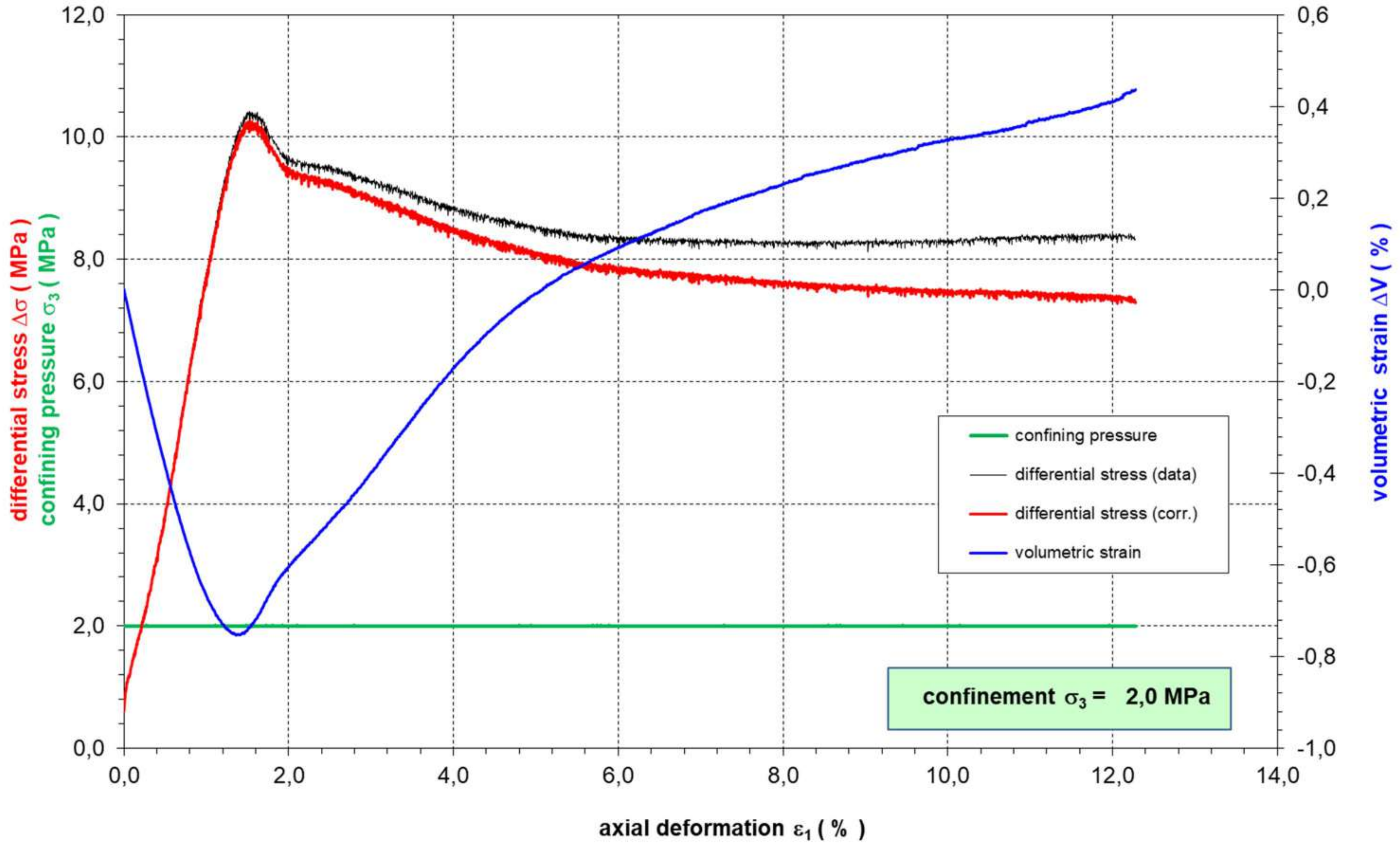
→ stress-strain behavior; sample 743/PAR073/TC_d1

Appendix 72

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength test (TC_nat)** **Unit – PAR (Poção Arenito)** → stress-strain behavior; sample 743/PAR072/TC_d2	**Appendix 73** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



INSTITUT FÜR GEBIRGSMECHANIK GMBH

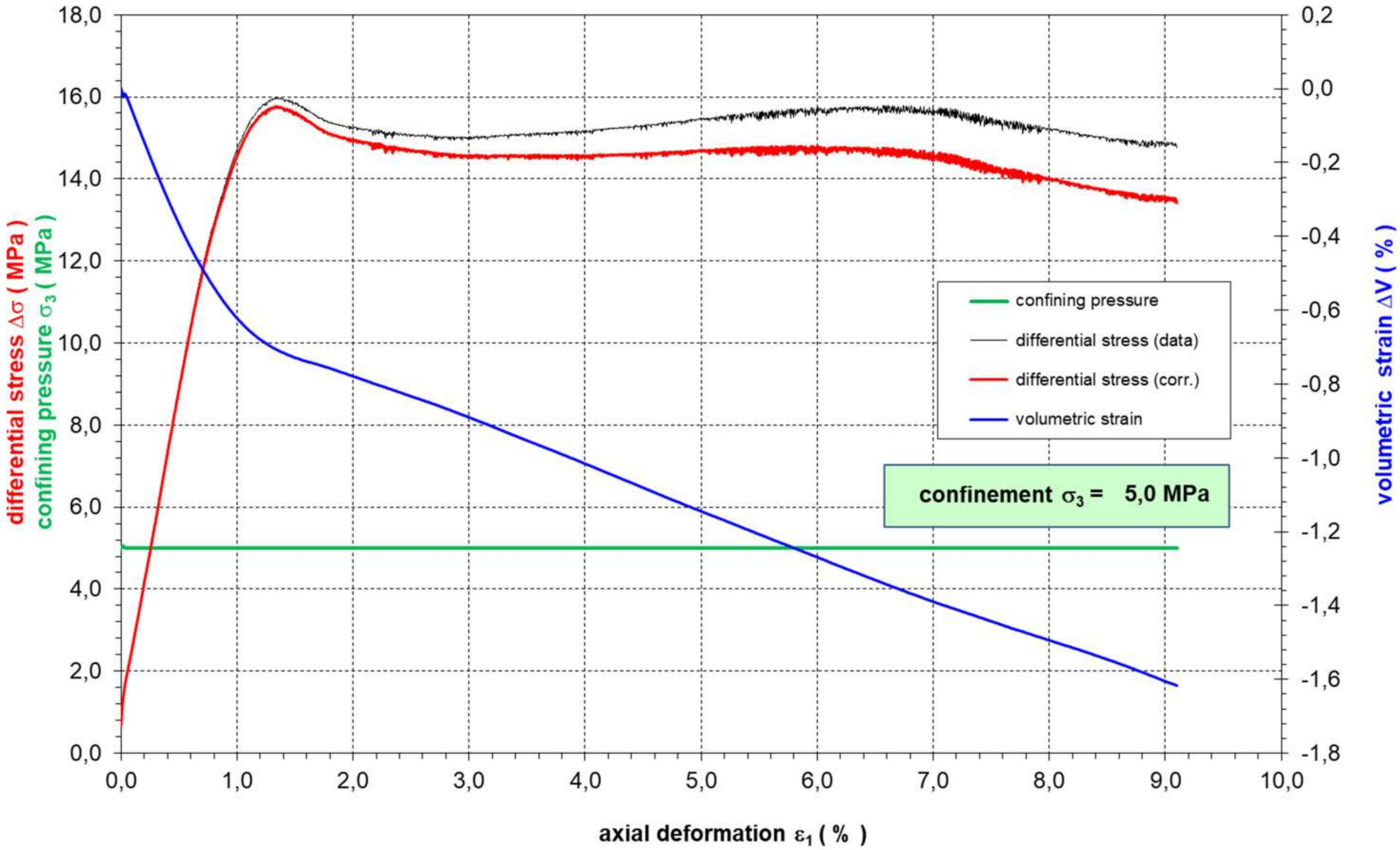
Triaxial strength test (TC_nat)

Unit – PAR (Poção Arenito)

→ stress-strain behavior; sample 743/PAR071/TC_d3

Appendix 74

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

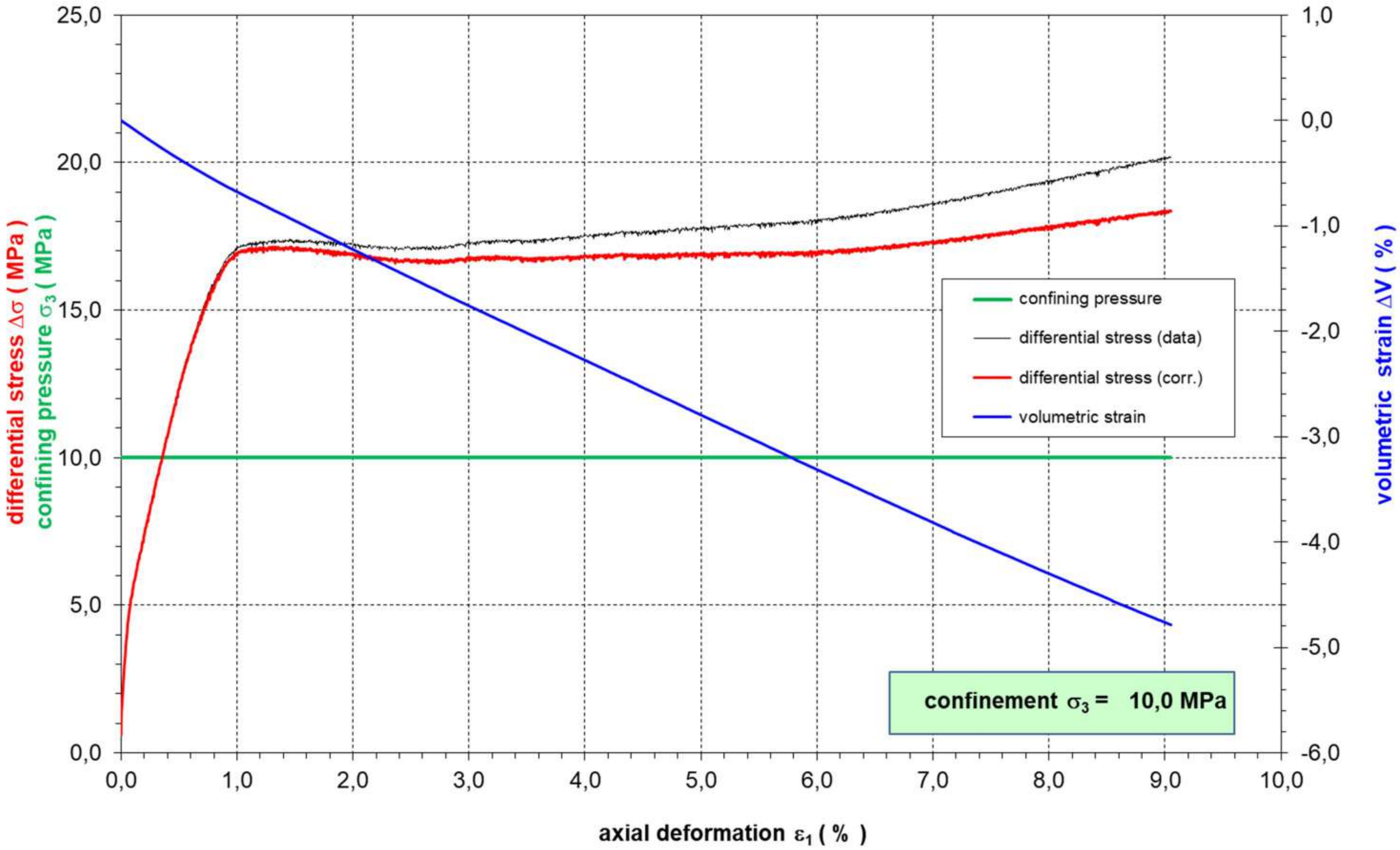
Triaxial strength test (TC_nat)

Unit – PAR (Poção Arenito)

→ stress-strain behavior; sample 743/PAR067/TC_d6

Appendix 75

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – PAR (Poção Arenito)

→ stress-strain behavior; sample 743/PAR079/TC_d7

Appendix 76

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	**9**	**9**		**6**	**6**	**3**	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Overview of planned tests

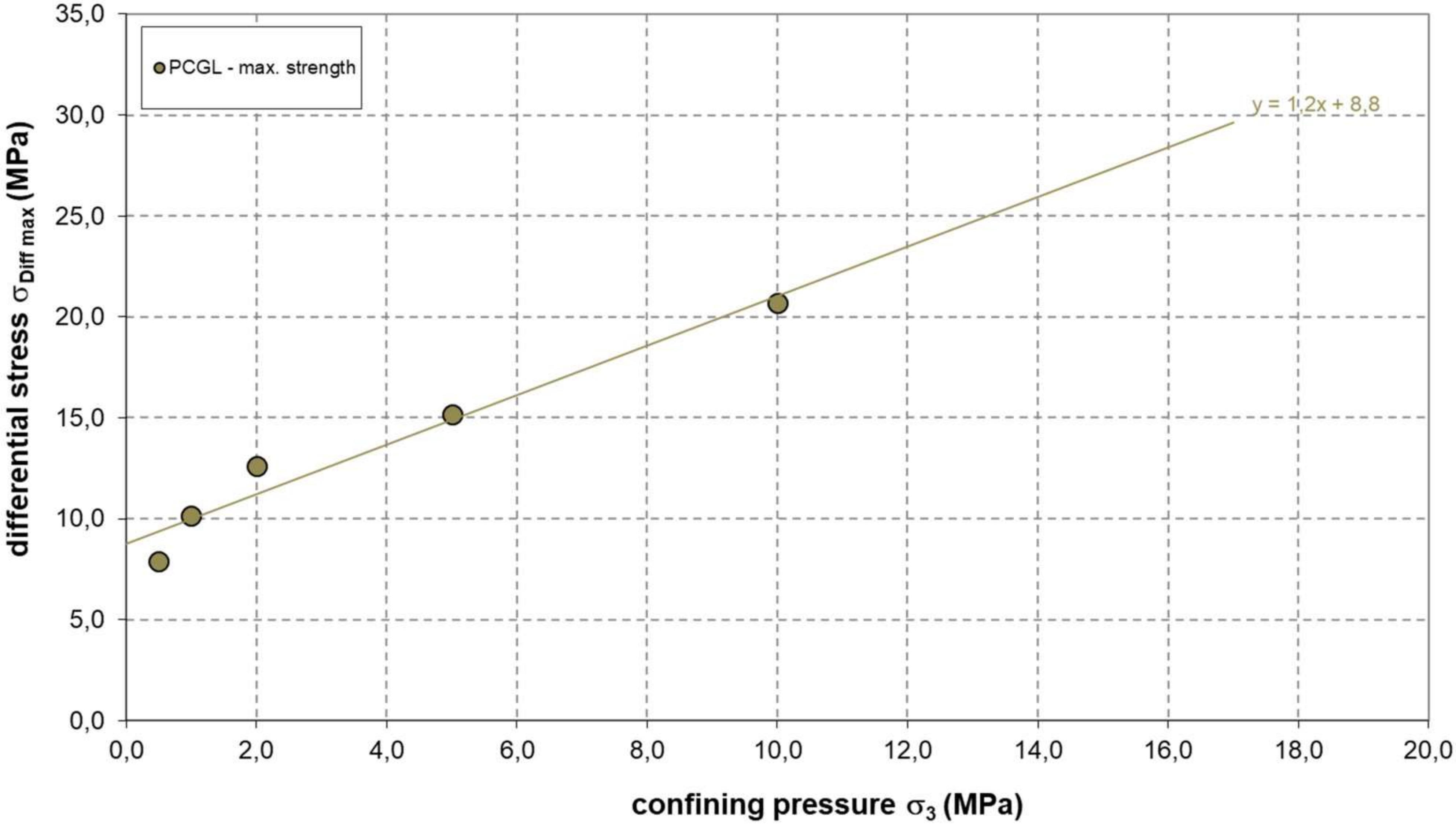
Unit – PCGL (Poção Conglomerado; Sandstone Matrix)

IfG - Lab-No.	743/PCGL050/TC_d1	743/PCGL049/TC_d2	743/PCGL048/TC_d3	743/PCGL045/TC_d4	743/PCGL046/TC_d5
Rock Type / Unit	PCGL	PCGL	PCGL	PCGL	PCGL
Sample	PCGL_050	PCGL_049	PCGL_048	PCGL_045	PCGL_046
Depth (m)					
Length l (mm) =	200.163	199.963	199.568	198.505	198.035
Diameter d (mm) =	100.730	100.673	100.700	100.682	100.698
Ratio l_o/d_o =	1.99	1.99	1.98	1.97	1.97
Mass M (g) =	3187.90	3187.4	3186.8	3202.3	3202.4
Area A (cm^2) =	79.691	79.601	79.643	79.615	79.640
Volume V (cm^3) =	1595.11	1591.72	1589.42	1580.39	1577.15
Density ρ (g/cm^3) =	1.999	2.002	2.005	2.026	2.030
US L (h) - p	-	-	-	-	-
US Q1 (a/c) - p	-	-	38.53	-	-
US Q2 (b/d) - p	-	-	-	-	-
US L (h) - s	-	-	-	-	-
US L (h) - p(s)	-	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	2.61	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-
E_d (GPa) =	-	-	-	-	-
K_d (GPa) =	-	-	-	-	-
G_d (GPa) =	-	-	-	-	-
ν_d =	-	-	-	-	-
	TC	**TC**	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**	**23**
σ_3 **(MPa) =**	0.5	1.0	2.0	5.0	10.0
σ_{Dil} **(MPa) =**	7.1	9.6	12.1	13.4	20.7
ΔV_{Dil} **(%) =**	-0.43	-0.56	-0.42	-1.63	-4.80
ε_{Dil} **(%) =**	0.68	0.78	0.71	7.21	9.99
σ_{Fail} **(MPa) =**	7.9	10.2	12.6	15.2	20.7
ΔV_{Fail} **(%) =**	-0.30	-0.52	-0.38	-0.54	-4.78
ε_{Fail} **(%) =**	0.86	0.90	0.84	0.85	9.95
σ_{1Fail} **(MPa) =**	8.38	11.17	14.63	20.16	30.69
α (°) =	65	65	65	65	65
σ_n **(MPa) =**	1.91	2.82	4.26	7.71	13.70
τ **(MPa) =**	3.02	3.89	4.84	5.81	7.92
ϕ=			**22.4**		
C=			**2.9**		

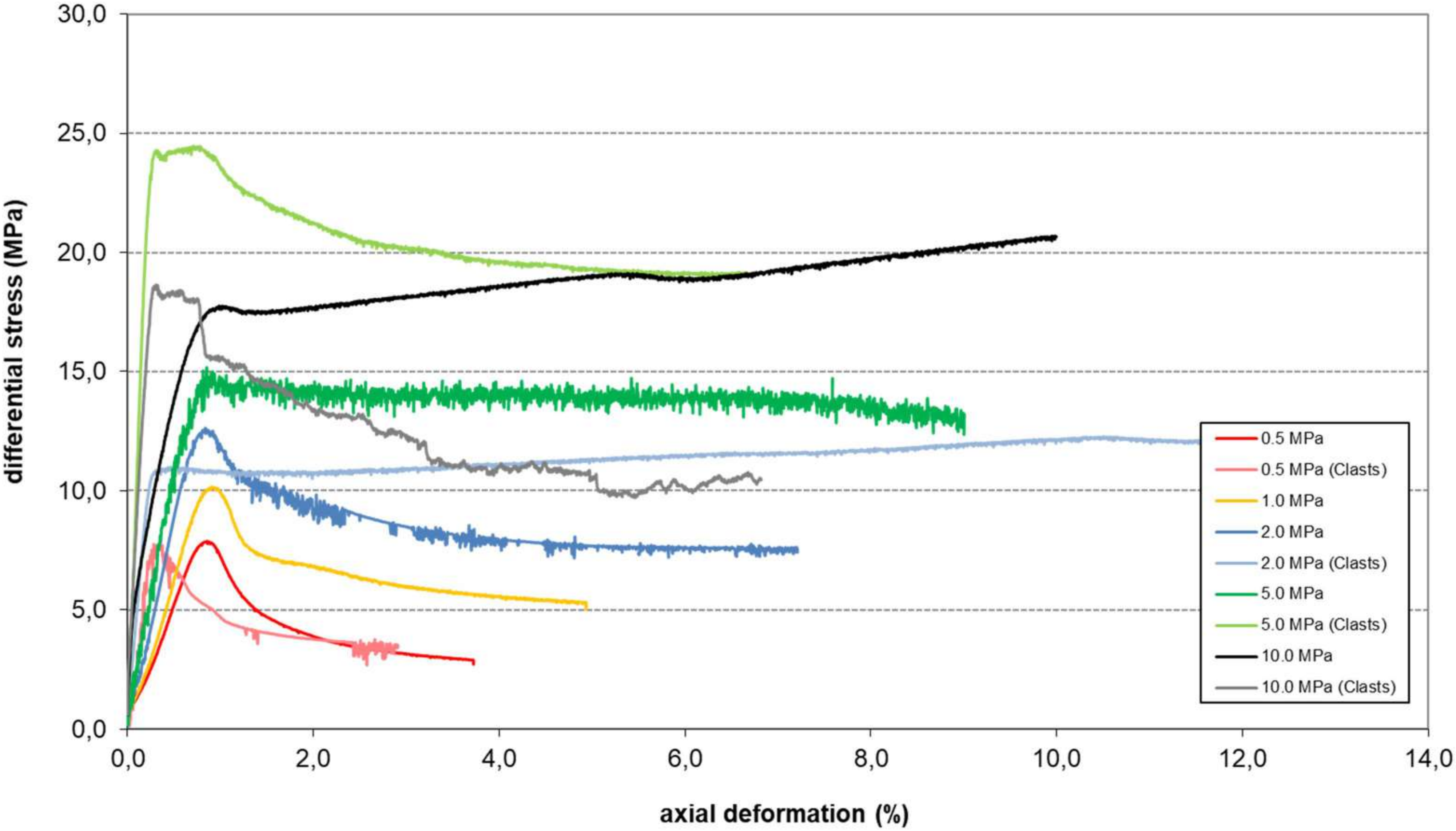
BEFORE:

AFTER:

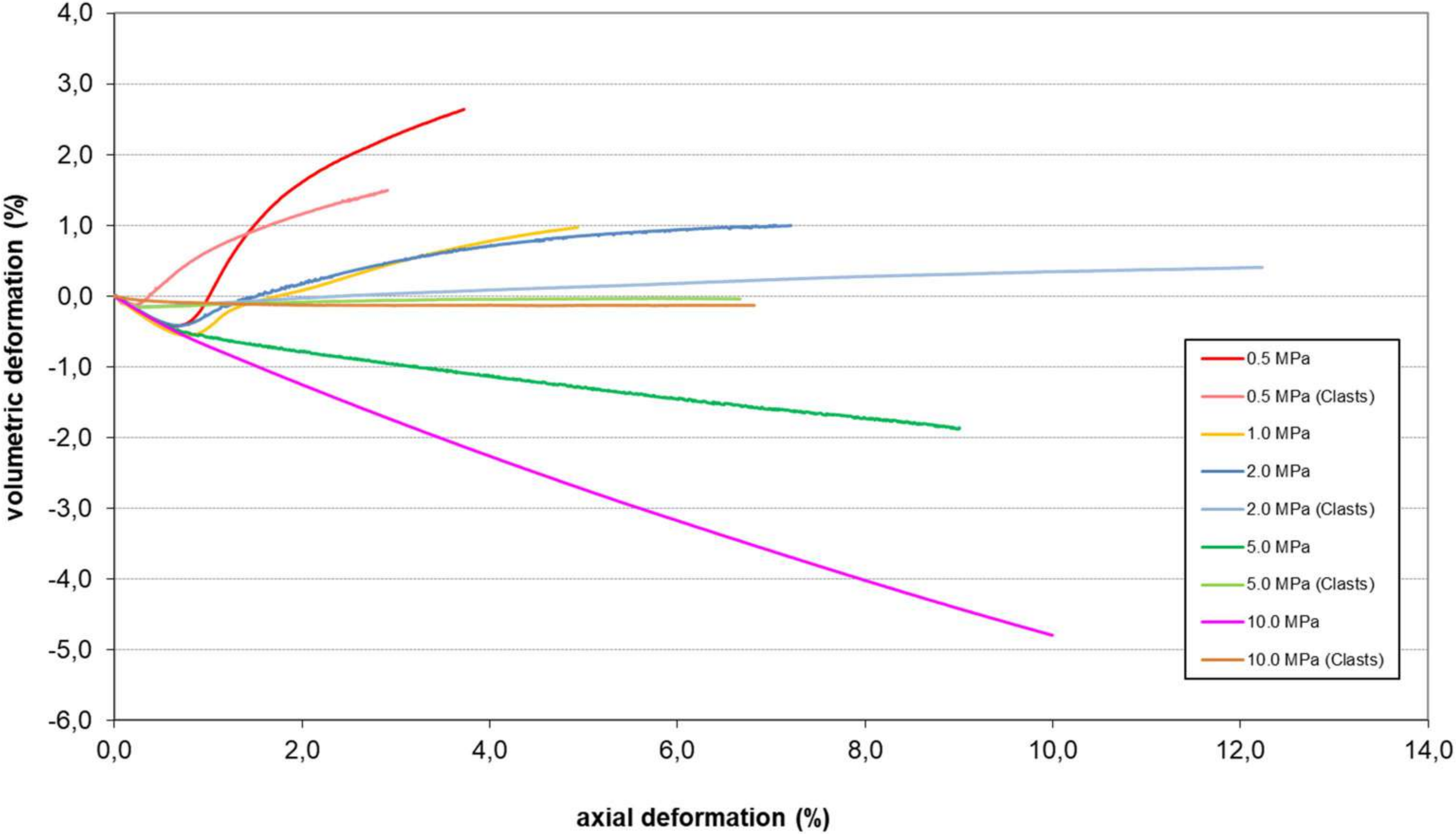
σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 2.0 MPa | σ_3 = 5.0 MPa | σ_3 = 10.0 MPa



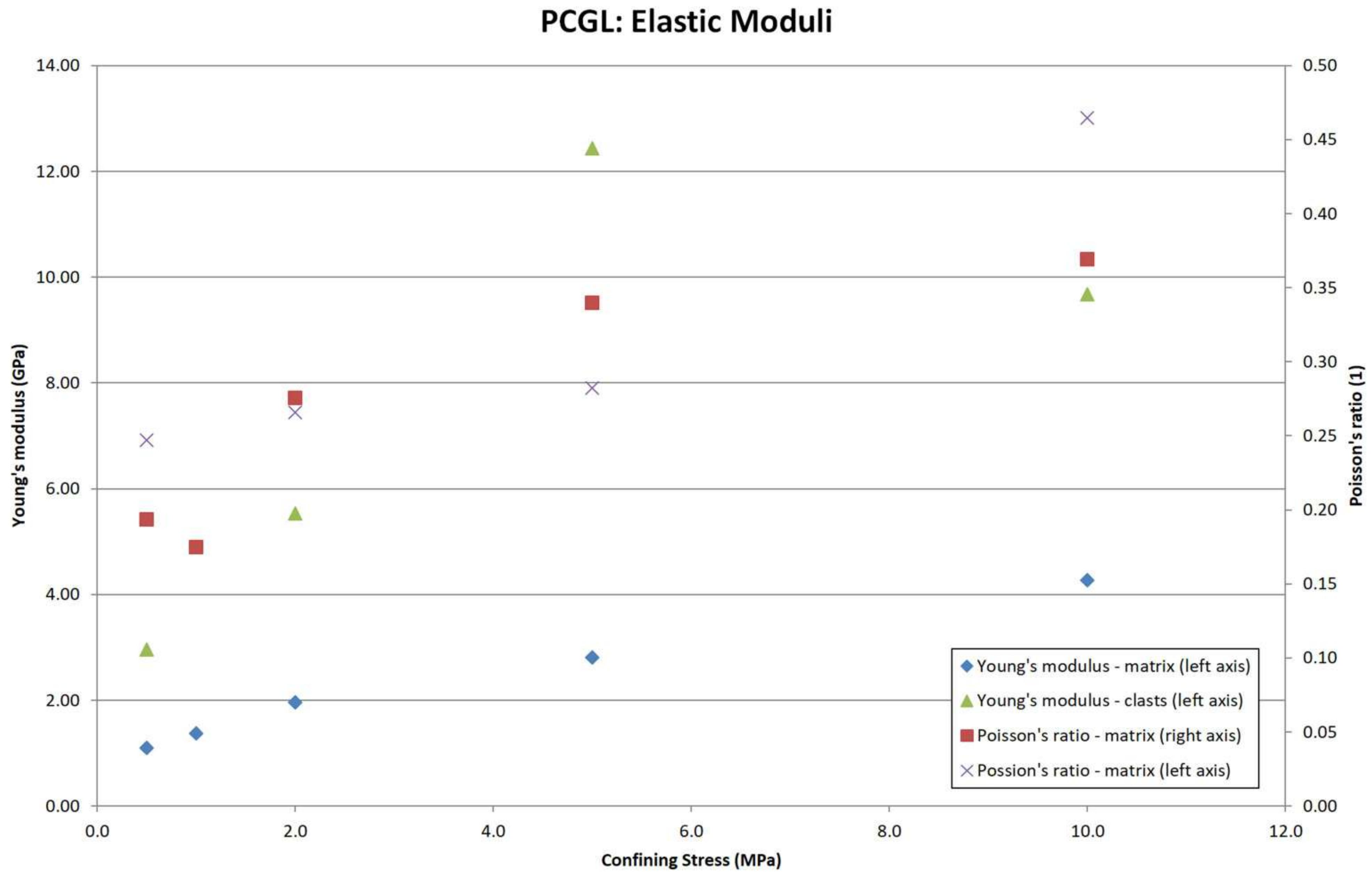
INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength tests (TC_nat)** **Unit – PCGL (Poção Conglomerado. Sandstone Matrix)** → maximum strength values dependent on the radial stress	**Appendix 80** ***B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”***



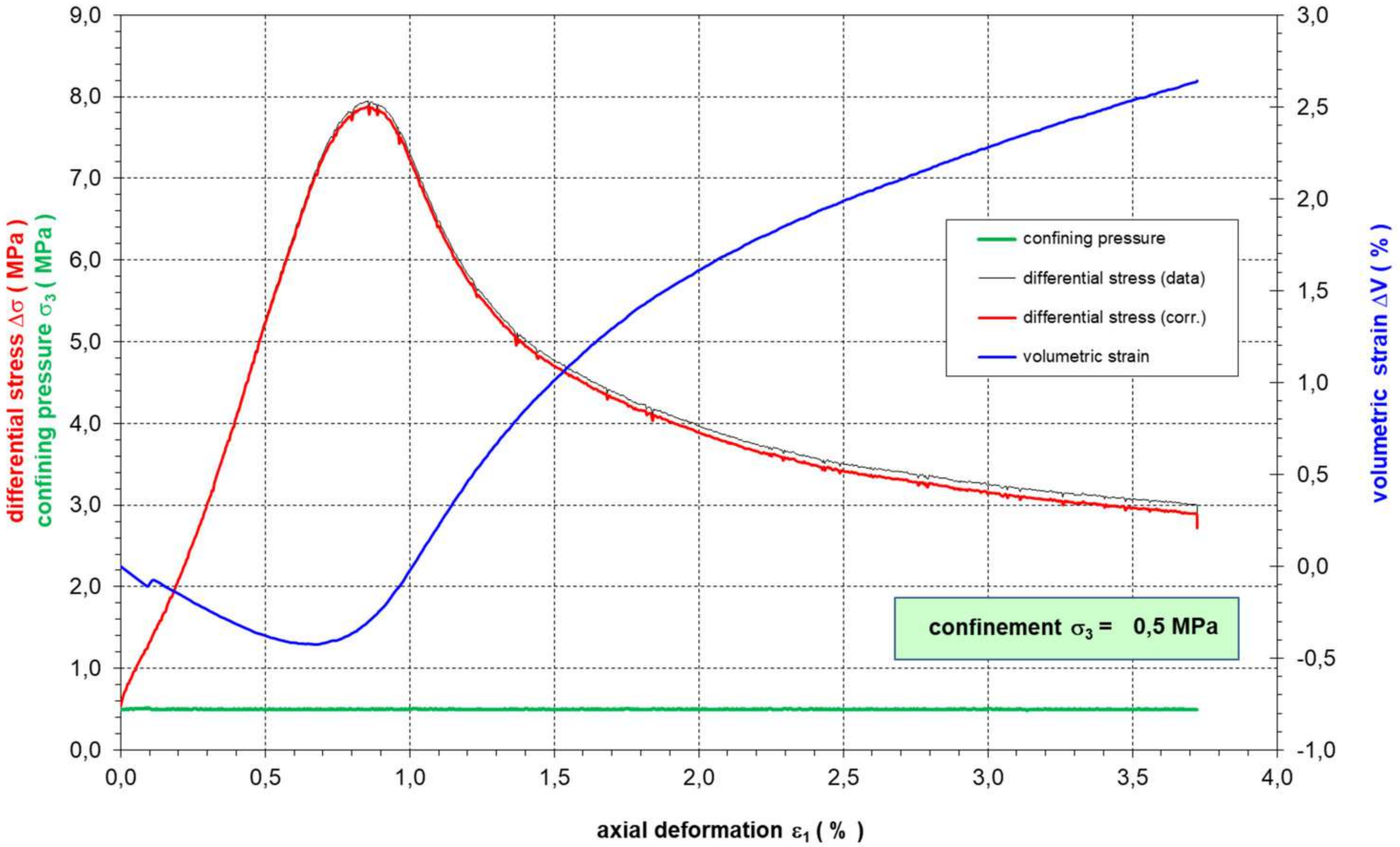
30,0
25,0
20,0
15,0
10,0
5,0
0,0
differential stress (MPa)
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
axial deformation (%)
0.5 MPa
0.5 MPa (Clasts)
1.0 MPa
2.0 MPa
2.0 MPa (Clasts)
5.0 MPa
5.0 MPa (Clasts)
10.0 MPa
10.0 MPa (Clasts)



4,0
3,0
2,0
1,0
0,0
-1,0
-2,0
-3,0
-4,0
-5,0
-6,0
volumetric deformation (%)
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
axial deformation (%)
0.5 MPa
0.5 MPa (Clasts)
1.0 MPa
2.0 MPa
2.0 MPa (Clasts)
5.0 MPa
5.0 MPa (Clasts)
10.0 MPa
10.0 MPa (Clasts)



PCGL: Elastic Moduli
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Young's modulus (GPa)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Poisson's ratio (1)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Confining Stress (MPa)
Young's modulus - matrix (left axis)
Young's modulus - clasts (left axis)
Poisson's ratio - matrix (right axis)
Possion's ratio - matrix (left axis)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

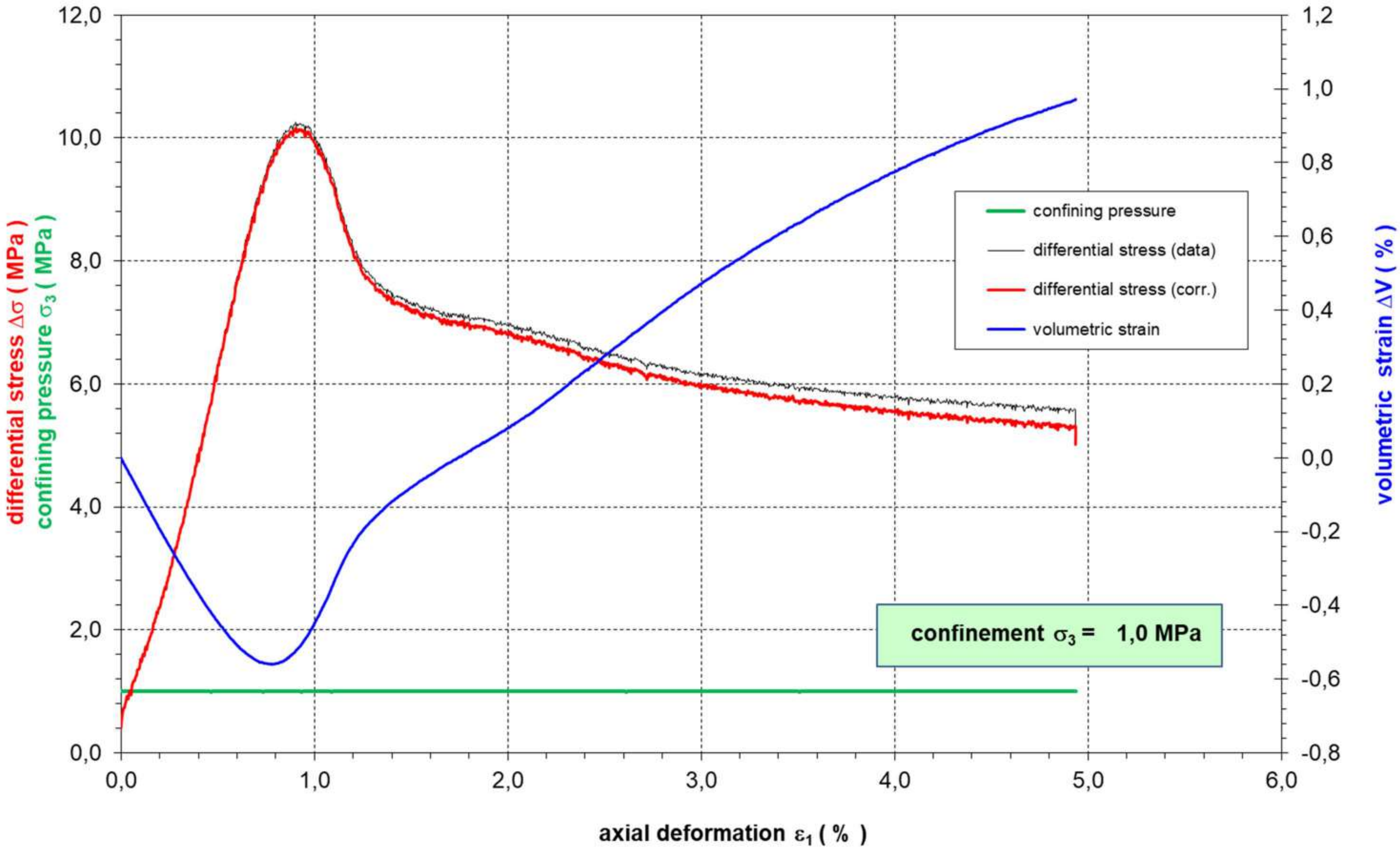
Triaxial strength test (TC_nat)

Unit – PCGL (Poção Conglomerado. Sandstone Matrix)

→ stress-strain behavior; sample 743/PCGL050/TC_d1

Appendix 84

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

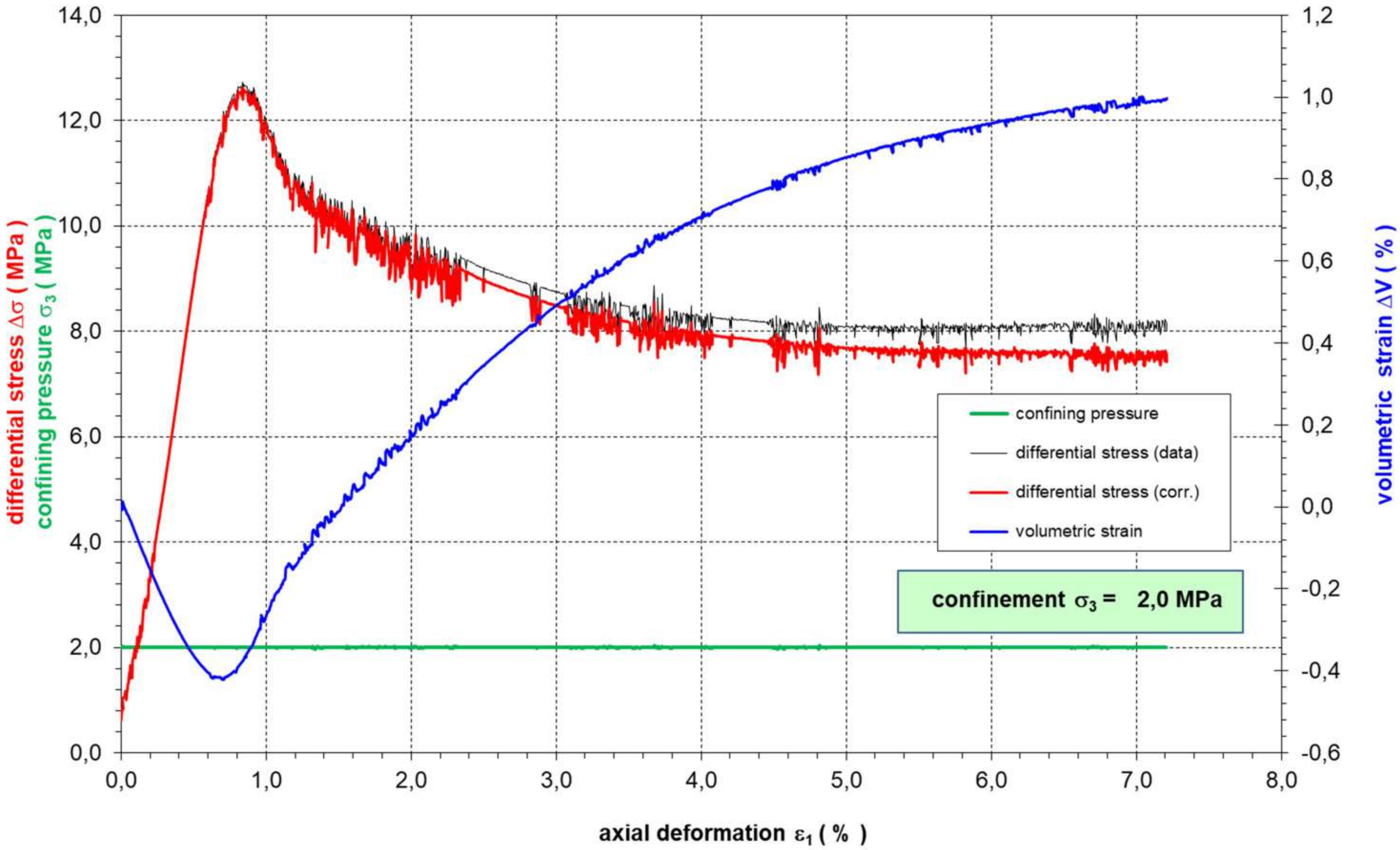
Triaxial strength test (TC_nat)

Unit – PCGL (Poção Conglomerado. Sandstone Matrix)

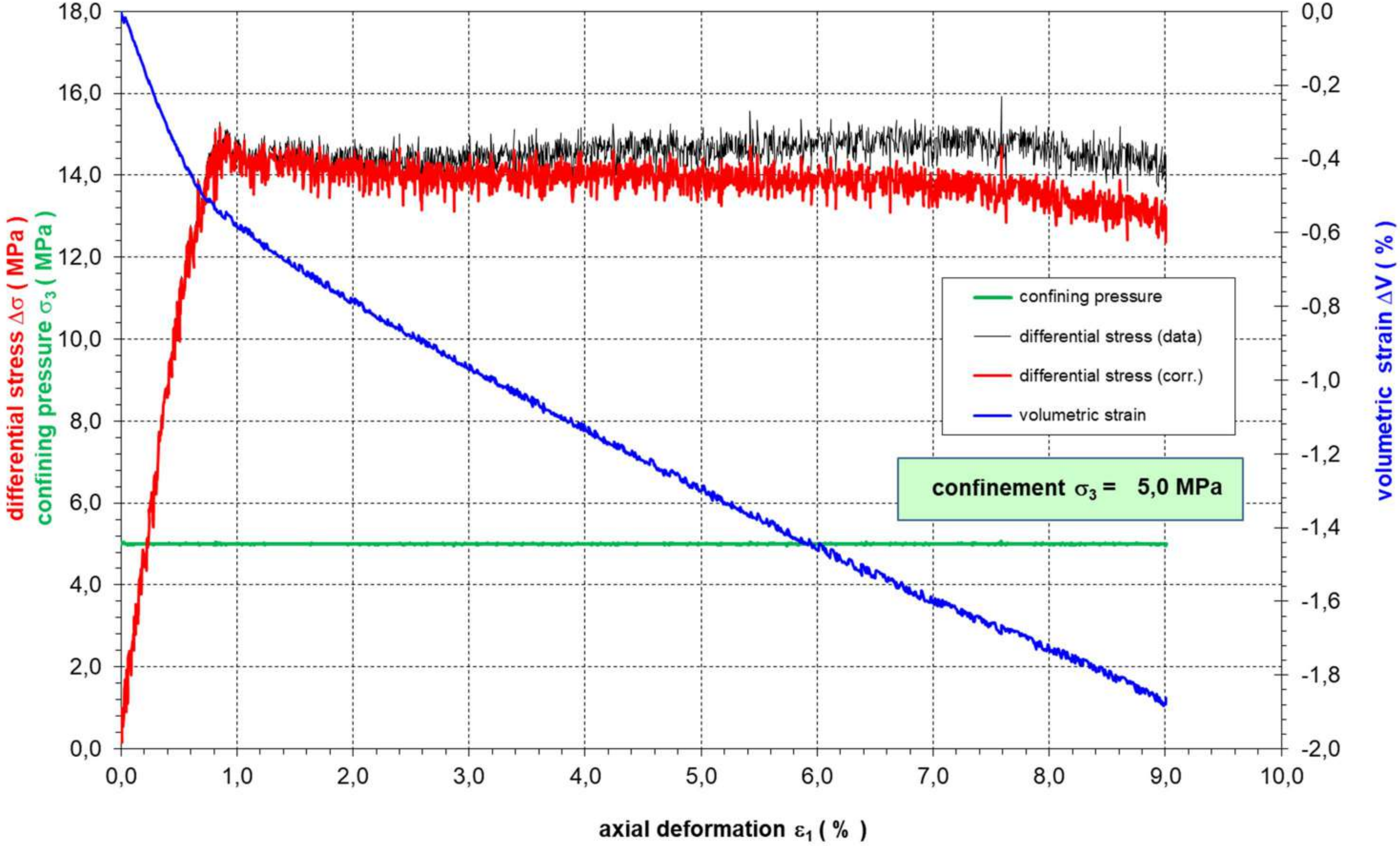
→ stress-strain behavior; sample 743/PCGL049/TC_d2

Appendix 85

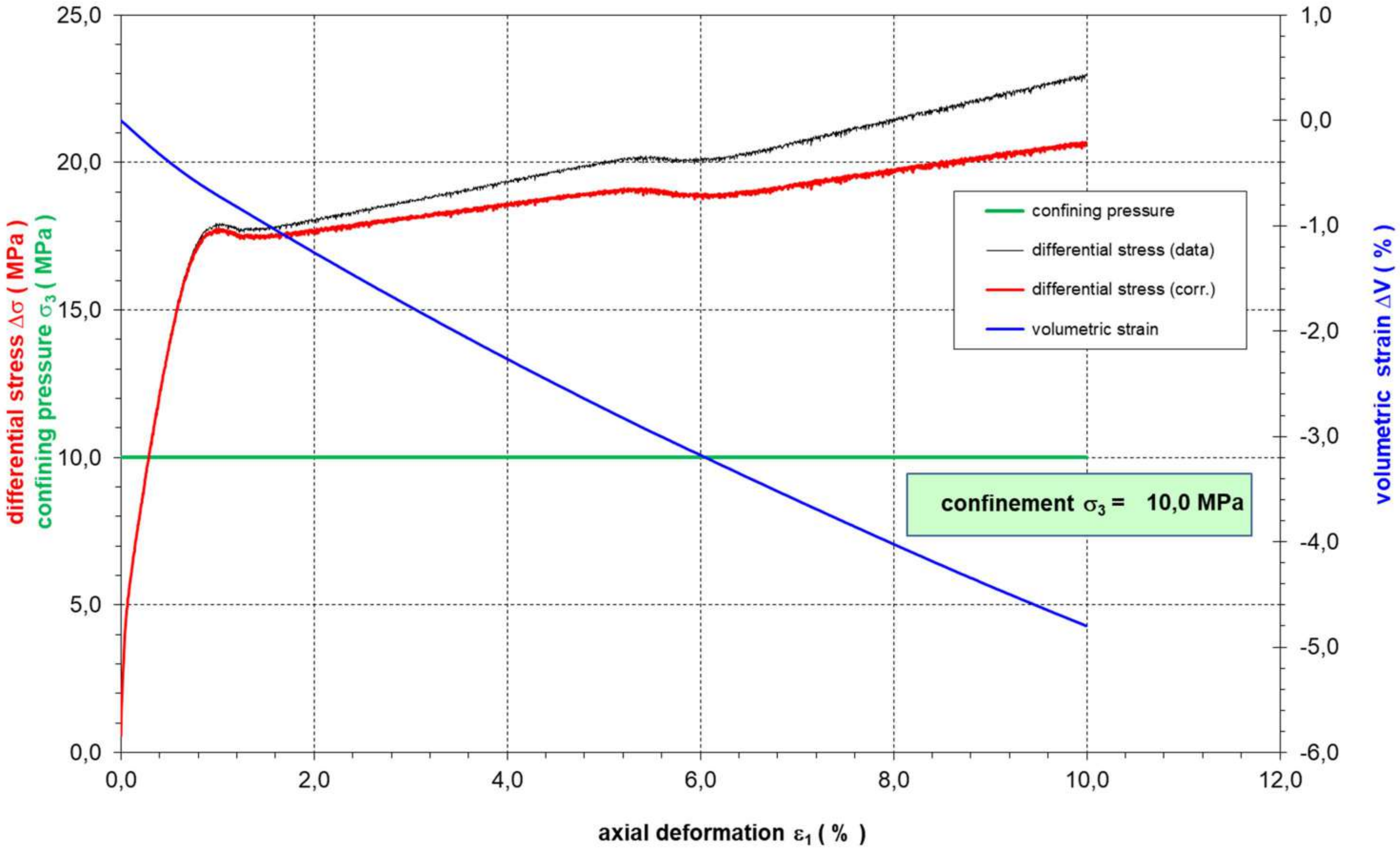
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength test (TC_nat)** **Unit – PCGL (Poção Conglomerado. Sandstone Matrix)** → stress-strain behavior; sample 743/PCGL048/TC_d3	**Appendix 86** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



18,0
16,0
14,0
12,0
10,0
8,0
6,0
4,0
2,0
0,0
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
-1,2
-1,4
-1,6
-1,8
-2,0
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 5,0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – PCGL (Poção Conglomerado. Sandstone Matrix)

→ stress-strain behavior; sample 743/PCGL46/TC_d5

Appendix 88

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	**9**	**9**		**6**	**6**	**3**	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/PCGL060/TC_d6	743/PCGL059/TC_d7	743/PCGL058/TC_d8	743/PCGL057/TC_d9
Rock Type / Unit	PCGL	PCGL	PCGL	PCGL
Sample	PCGL_060	PCGL_059	PCGL_058	PCGL_057
Depth (m)				
Length l (mm) =	203.655	199.608	200.493	170.685
Diameter d (mm) =	100.493	100.672	100.643	100.663
Ratio l_o/d_o =	2.03	1.98	1.99	1.70
Mass M (g) =	3710.3	3798.7	3848.6	3278.2
Area A (cm^2) =	79.316	79.599	79.553	79.585
Volume V (cm^3) =	1615.31	1588.86	1594.98	1358.39
Density ρ (g/cm^3) =	2.297	2.391	2.413	2.413
US L (h) - p	-	-	-	-
US Q1 (a/c) - p	-	-	-	-
US Q2 (b/d) - p	-	-	-	-
US L (h) - s	-	-	-	-
US L (h) - p(s)	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-
E_d (GPa) =	-	-	-	-
K_d (GPa) =	-	-	-	-
G_d (GPa) =	-	-	-	-
ν_d =	-	-	-	-
	TC	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.5	2.0	5.0	10.0
σ_{Dil} (MPa) =	7.0	10.8	24.0	10.9
ΔV_{Dil} (%) =	-0.13	-0.15	-0.16	-0.14
ε_{Dil} (%) =	0.22	0.29	0.28	4.54
σ_{Fail} (MPa) =	7.8	12.3	24.5	18.6
ΔV_{Fail} (%) =	-0.10	0.36	-0.14	-0.06
ε_{Fail} (%) =	0.28	10.50	0.71	0.31
σ_{1Fail} (MPa) =	8.26	14.27	29.47	28.64
α (°) =	65	65	65	65
σ_n (MPa) =	1.89	4.19	9.37	13.33
τ (MPa) =	2.97	4.70	9.37	7.14
ϕ=	**21.5**			
C=	**3.7**			

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

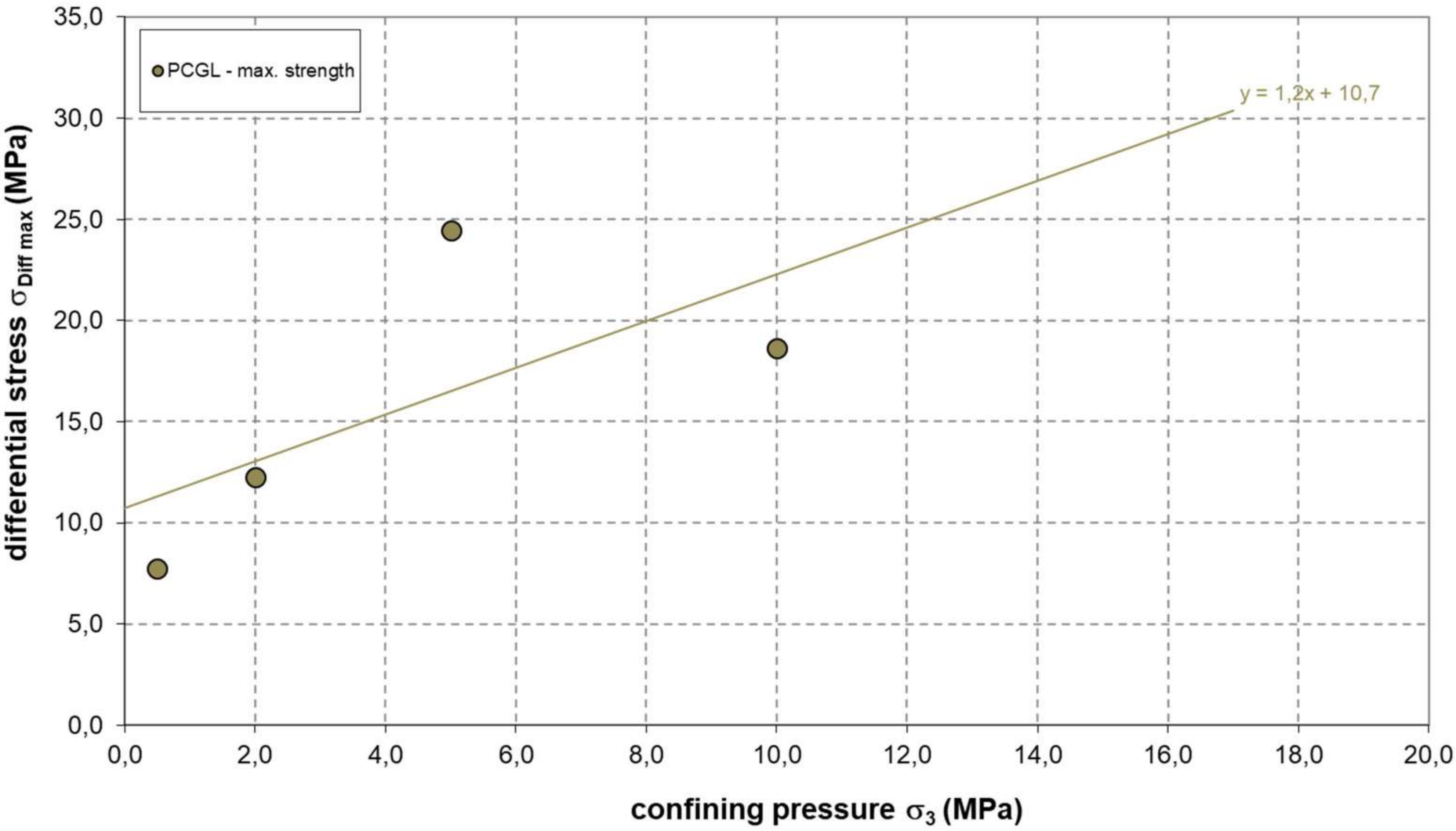
Unit – PCGL (Poção Conglomerado. with clasts)

→ petrophysical parameters and stress-strain-values

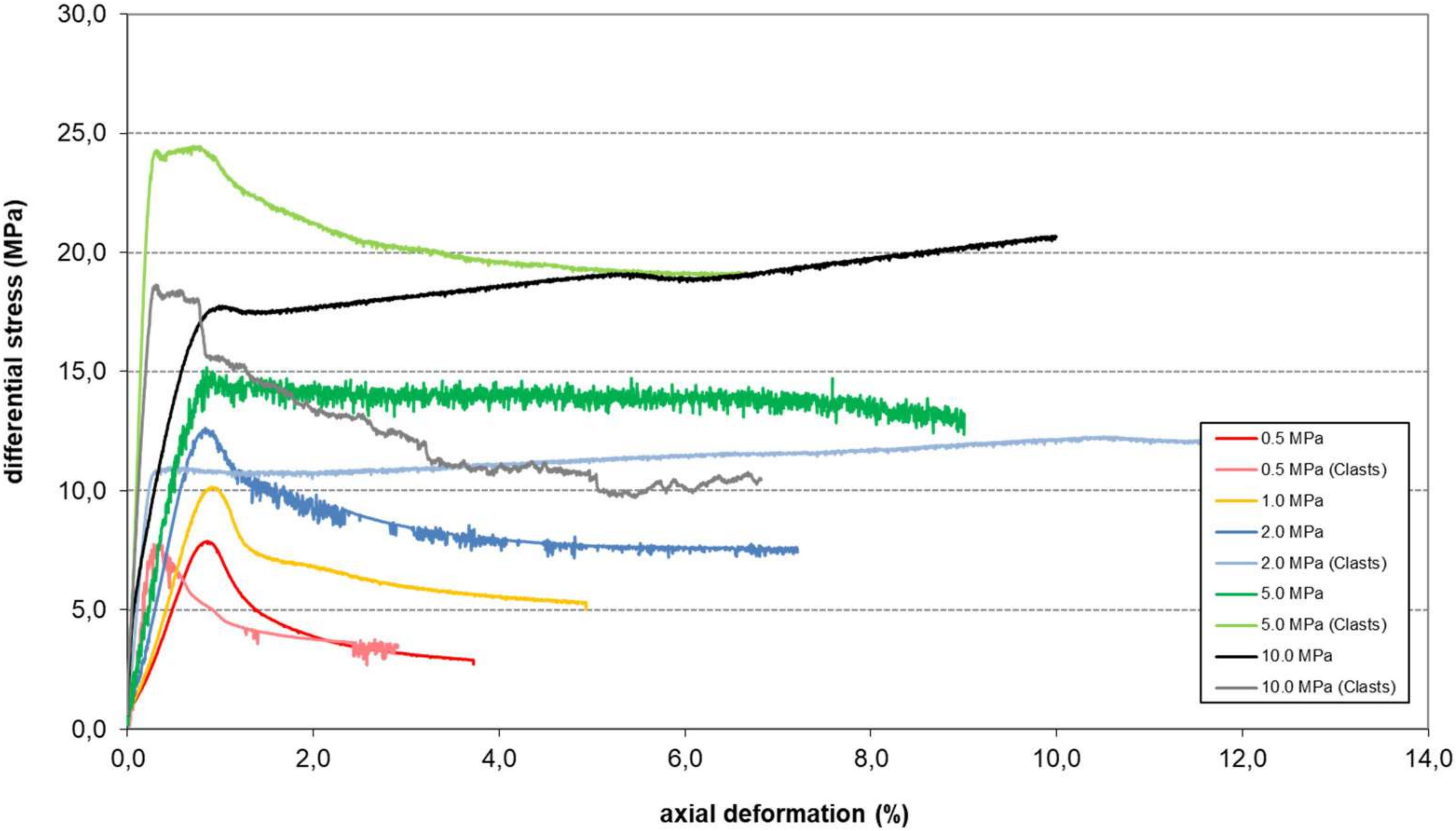
BEFORE:

AFTER:

σ_3 = 0.5 MPa | σ_3 = 2.0 MPa | σ_3 = 5.0 MPa | σ_3 = 10.0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength tests (TC_nat)** **Unit – PCGL (Poção Conglomerado. with clasts)** → maximum strength values dependent on the radial stress	**Appendix 92** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



INSTITUT FÜR GEBIRGSMECHANIK GMBH

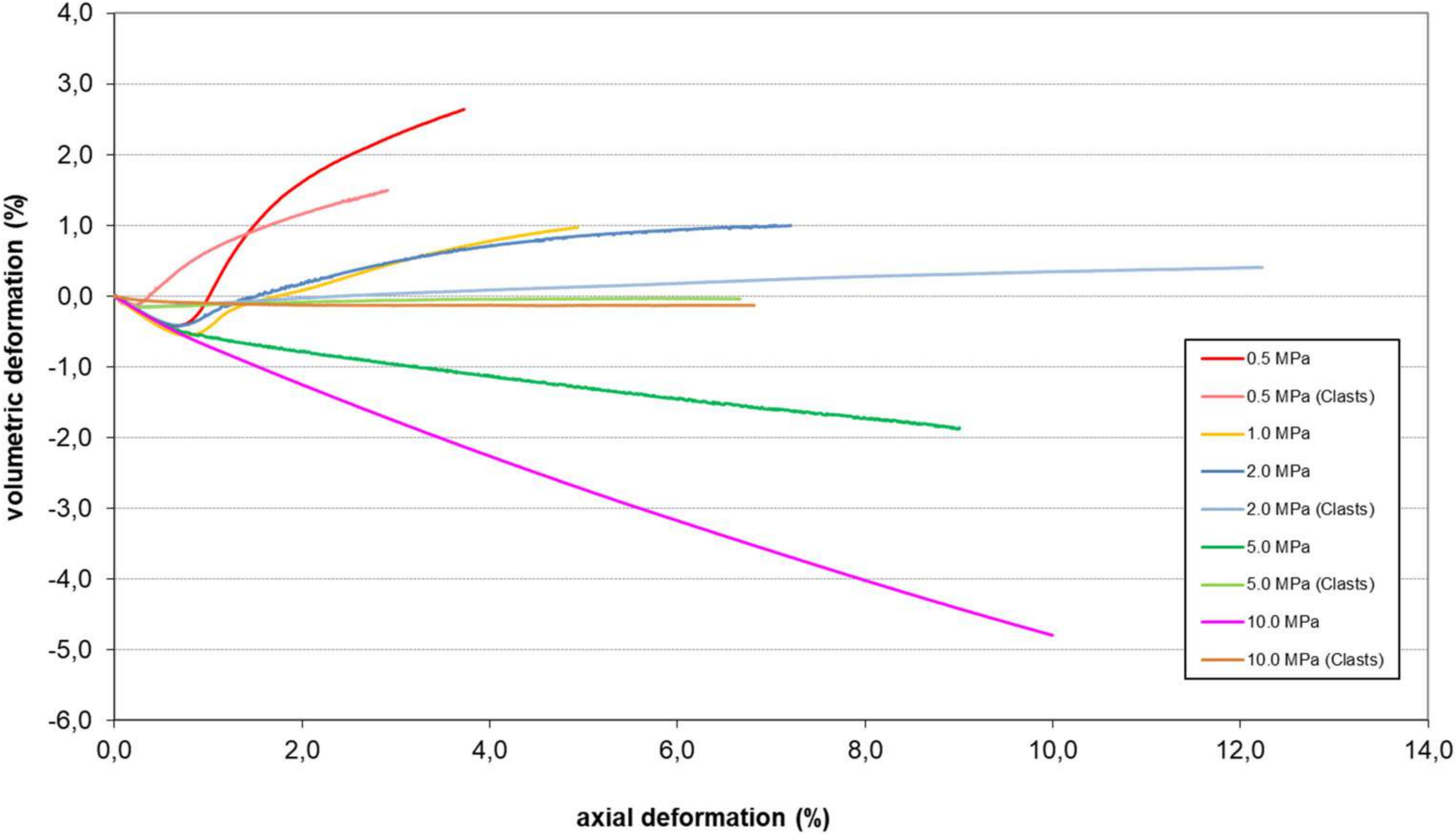
Triaxial strength tests (TC_nat)

Unit – PCGL (Poção Conglomerado. with clasts)

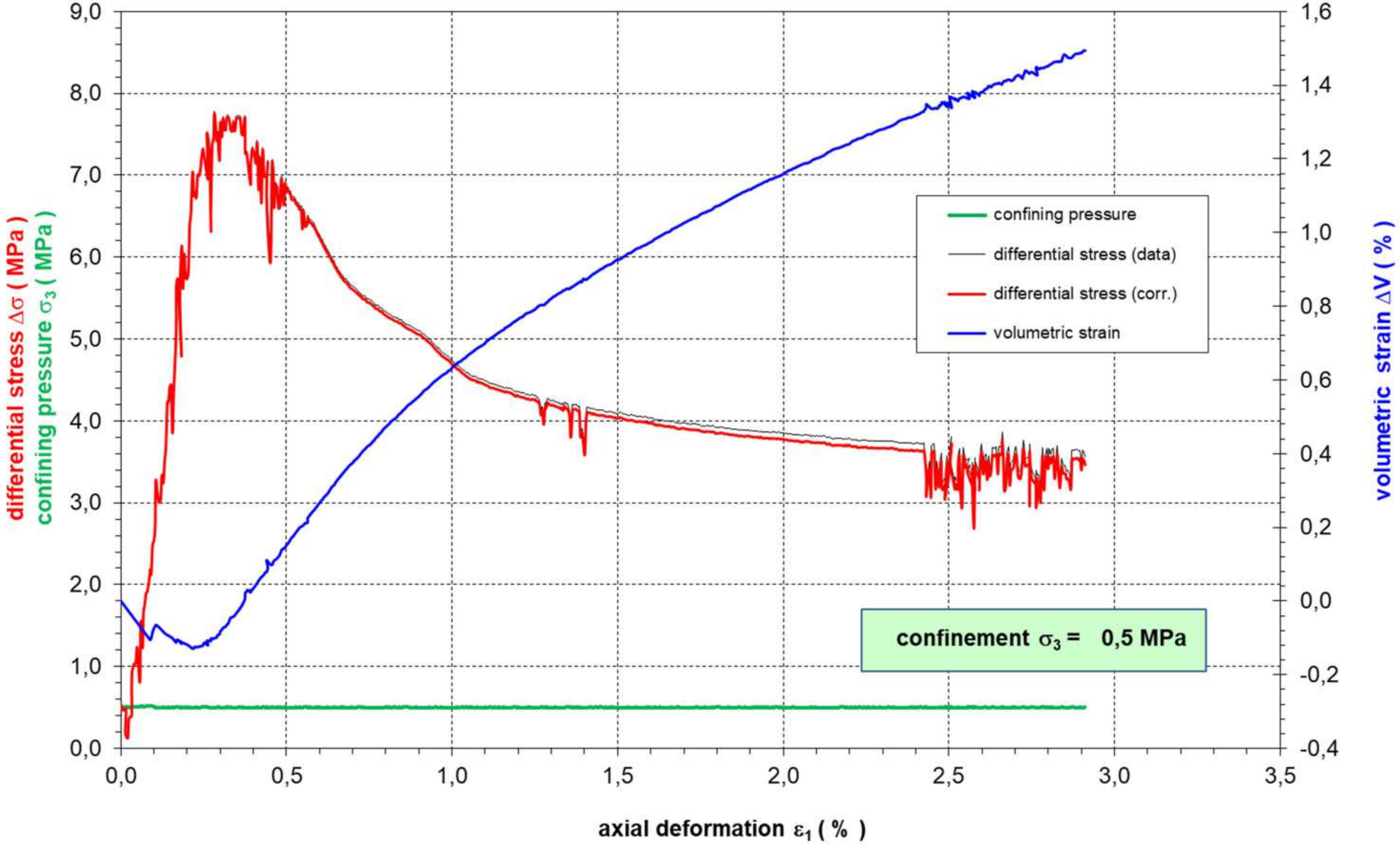
→ stress-strain curves of all tests

Appendix 93

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



4,0
3,0
2,0
1,0
0,0
-1,0
-2,0
-3,0
-4,0
-5,0
-6,0
volumetric deformation (%)
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
axial deformation (%)
0.5 MPa
0.5 MPa (Clasts)
1.0 MPa
2.0 MPa
2.0 MPa (Clasts)
5.0 MPa
5.0 MPa (Clasts)
10.0 MPa
10.0 MPa (Clasts)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

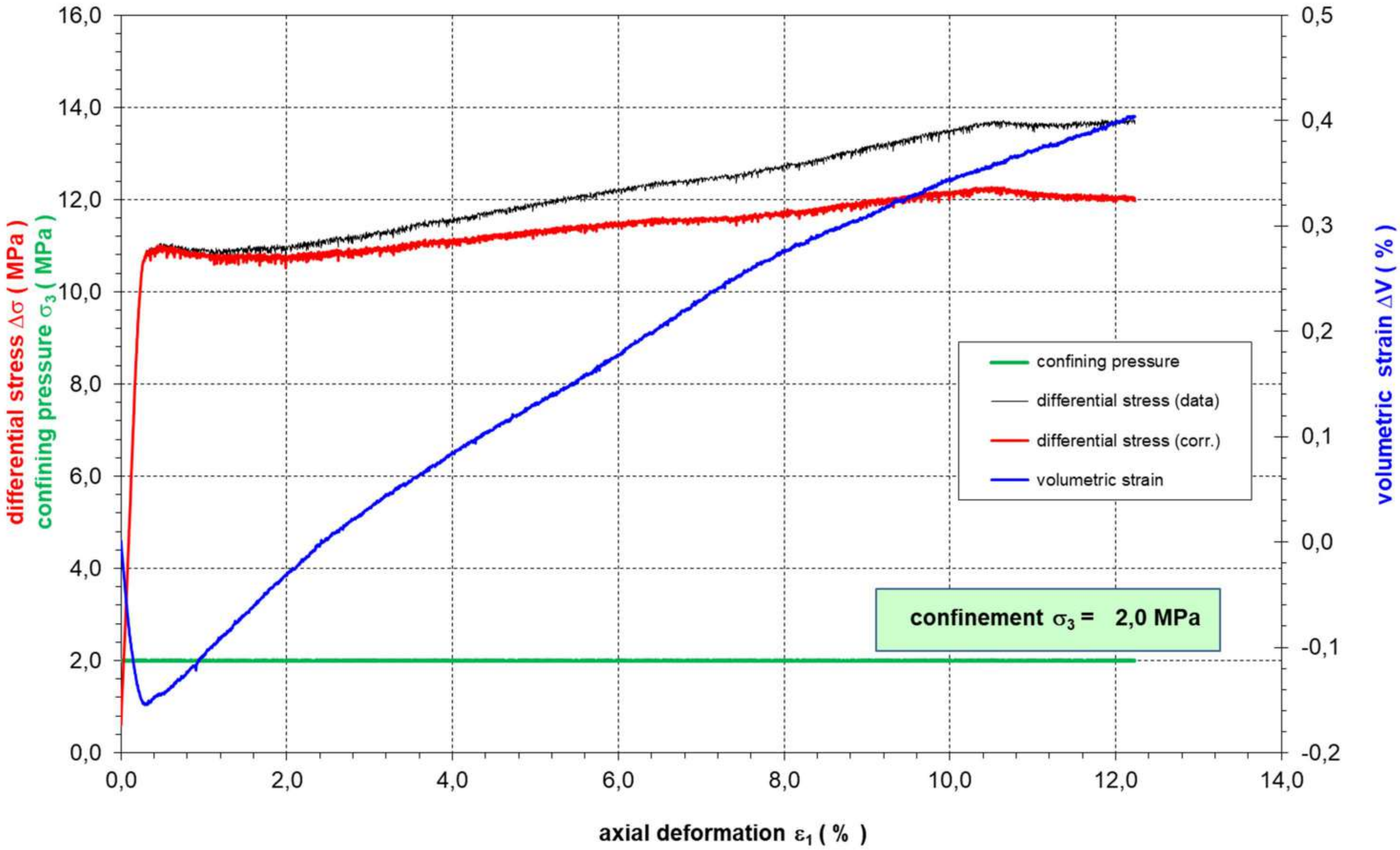
Triaxial strength test (TC_nat)

Unit – PCGL (Poção Conglomerado. with clasts)

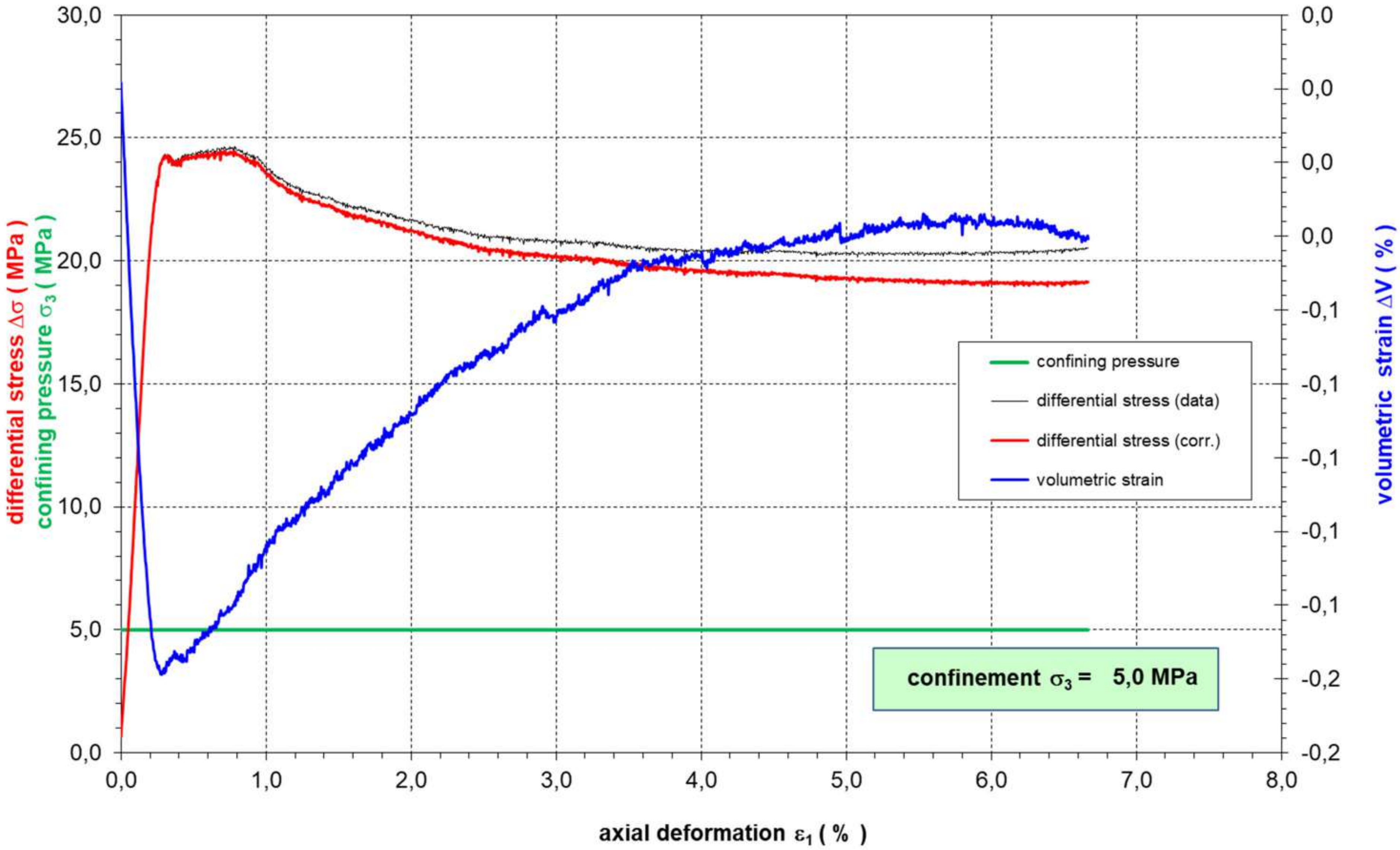
→ stress-strain behavior; sample 743/PCGL060/TC_d6

Appendix 95

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



16,0
14,0
12,0
10,0
8,0
6,0
4,0
2,0
0,0
0,5
0,4
0,3
0,2
0,1
0,0
-0,1
-0,2
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 2,0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

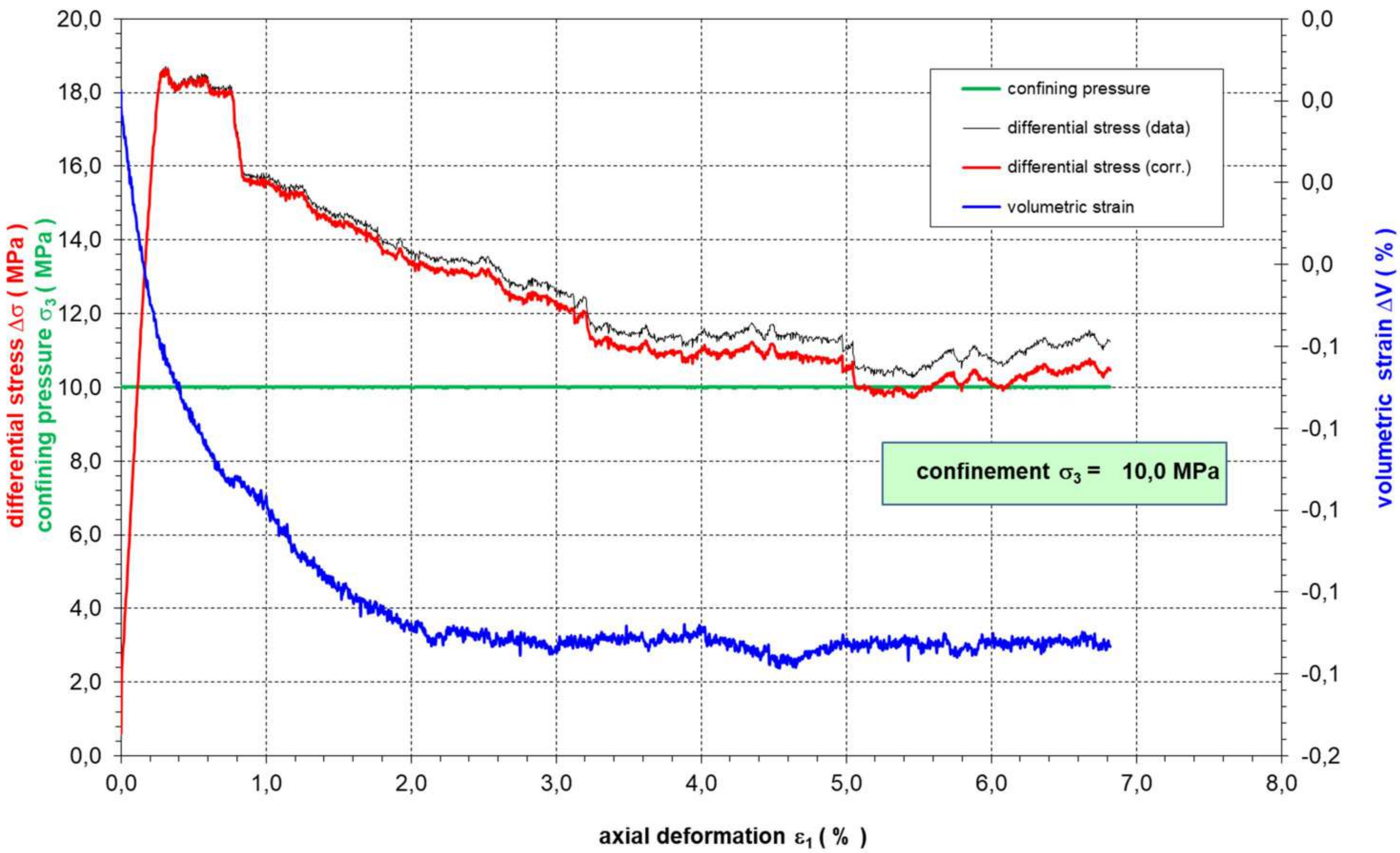
Triaxial strength test (TC_nat)

Unit – PCGL (Poção Conglomerado. with clasts)

→ stress-strain behavior; sample 743/PCGL058/TC_d8

Appendix 97

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

Triaxial strength test (TC_nat)

Unit – PCGL (Poção Conglomerado. with clasts)

→ stress-strain behavior; sample 743/PCGL058/TC_d9

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	**9**	**9**		**6**	**6**	**3**	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Overview of planned tests

Unit – PI (Poção Intercalado)

Appendix 99

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

IfG - Lab-No.	743/PI001/TC_d1	743/PI002/TC_d2	743/PI003/TC_d3	743/PI006/TC_d4
Rock Type / Unit	PI	PI	PI	PI
Sample	PI_001	PI_002	PI_003	PI_006
Depth (m)				
Length l (mm) =	198.105	200.375	198.268	198.920
Diameter d (mm) =	99.798	100.197	99.557	99.053
Ratio l_o/d_o =	1.99	2.00	1.99	2.01
Mass M (g) =	3036.80	3123.7	2845.6	2967.1
Area A (cm²) =	78.223	78.850	77.845	77.059
Volume V (cm³) =	1549.63	1579.95	1543.43	1532.86
Density ρ (g/cm^3) =	1.960	1.977	1.844	1.936
US L (h) - p	-	-	-	-
US Q1 (a/c) - p	-	-	-	-
US Q2 (b/d) - p	-	-	-	-
US L (h) - s	-	-	-	-
US L (h) - p(s)	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-
E_d (GPa) =	-	-	-	-
K_d (GPa) =	-	-	-	-
G_d (GPa) =	-	-	-	-
ν_d =	-	-	-	-
	TC	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.5	1.0	2.0	5.0
σ_{Dil} (MPa) =	5.4	6.9	10.6	12.2
ΔV_{Dil} (%) =	-0.27	-0.29	-0.32	-1.75
ε_{Dil} (%) =	0.50	0.45	0.63	5.46
σ_{Fail} (MPa) =	6.4	8.8	11.8	15.2
ΔV_{Fail} (%) =	-0.12	-0.19	-0.27	-0.50
ε_{Fail} (%) =	0.79	0.67	0.81	0.92
σ_{1Fail} (MPa) =	6.94	9.78	13.83	20.24
α (°) =	65	65	65	65
σ_n (MPa) =	1.65	2.57	4.11	7.72
τ (MPa) =	2.47	3.36	4.53	5.84
ϕ=	**28.3**			
C=	**2.0**			

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

Unit – PI (Poção Intercalado)

→ petrophysical parameters and stress-strain-values

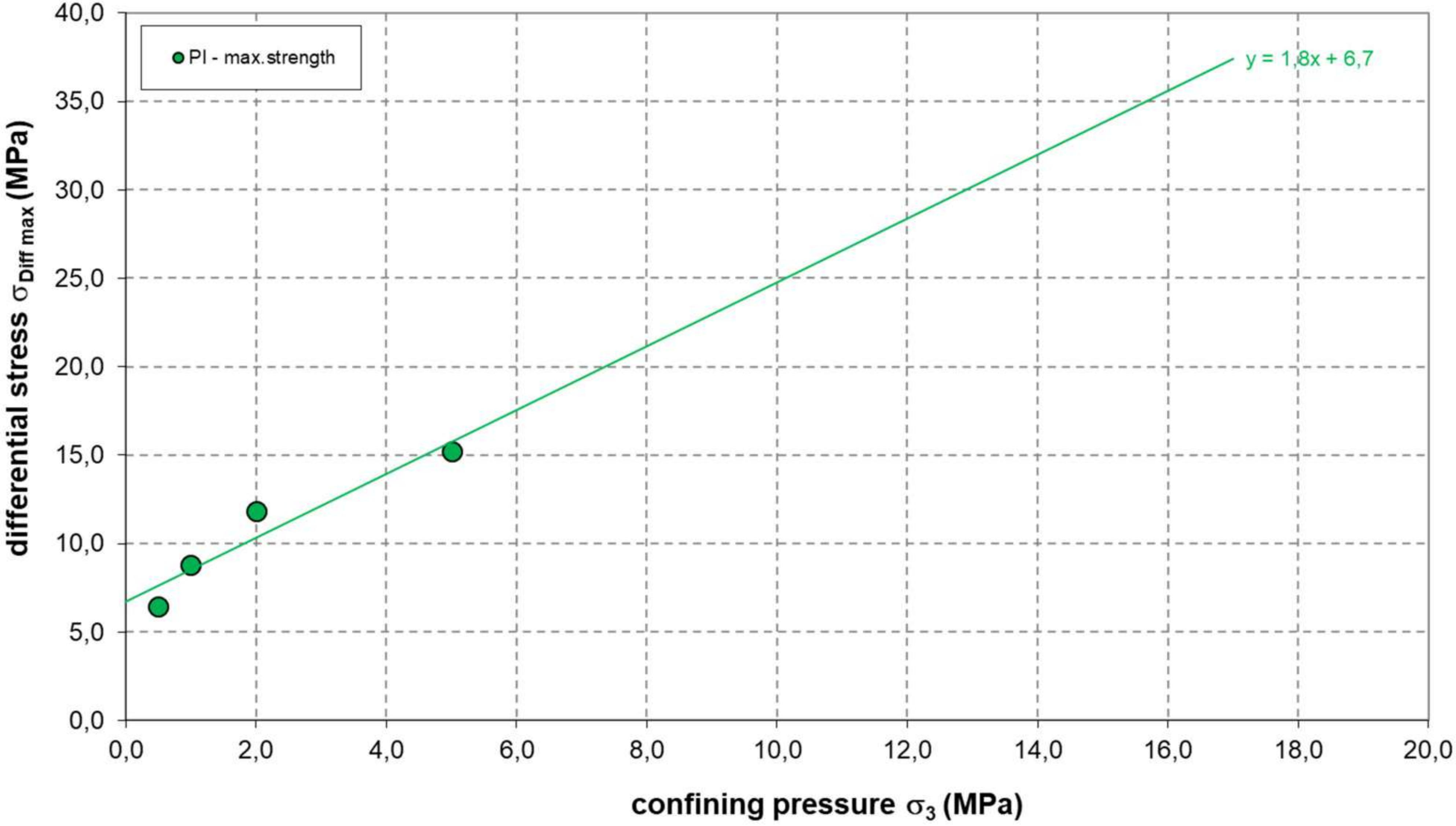
Appendix 100

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:

AFTER:

σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 2.0 MPa | σ_3 = 5.0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

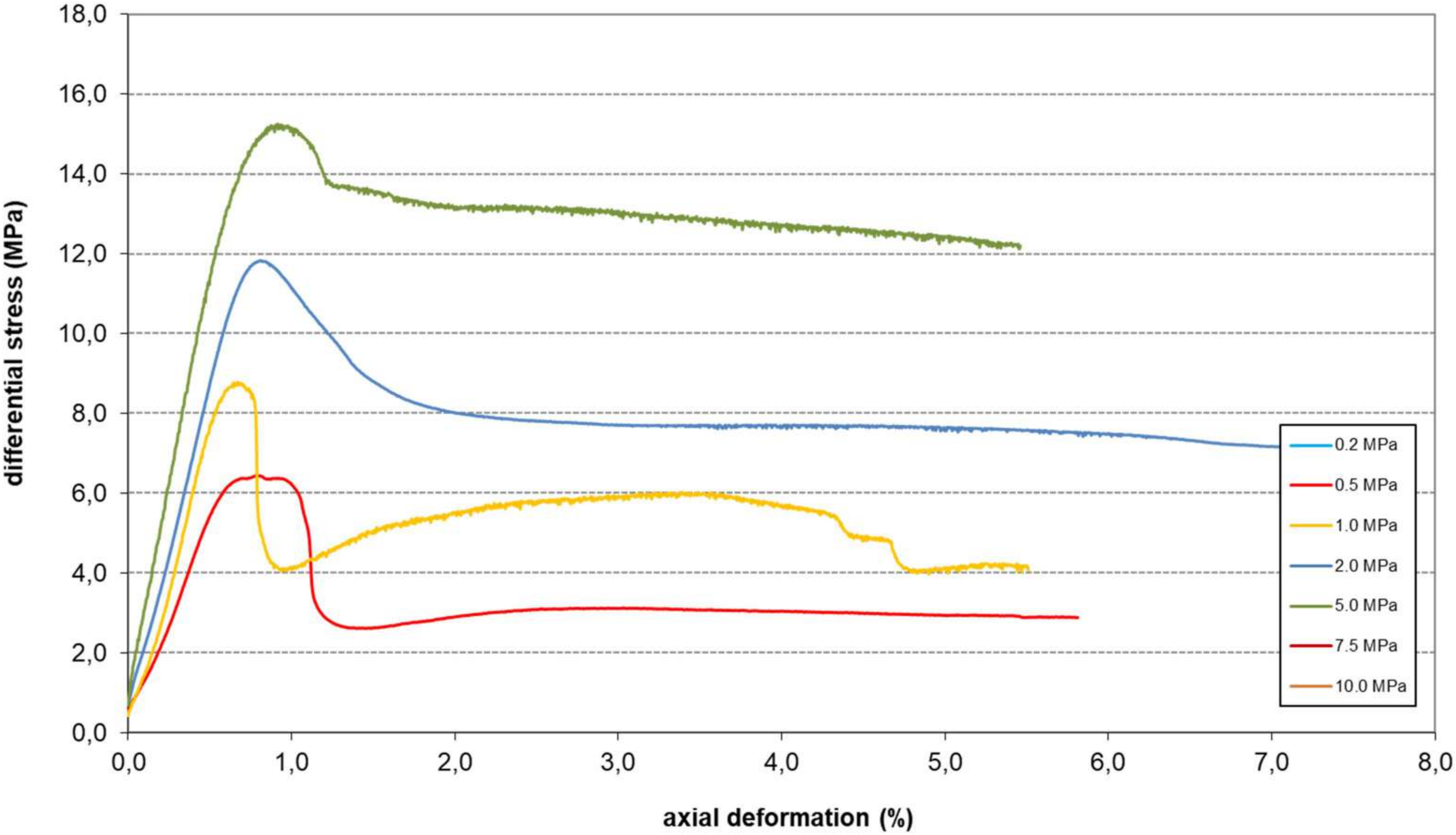
Triaxial strength tests (TC_nat)

Unit – PI (Poção Intercalado)

→ maximum strength values dependent on the radial stress

Appendix 102

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

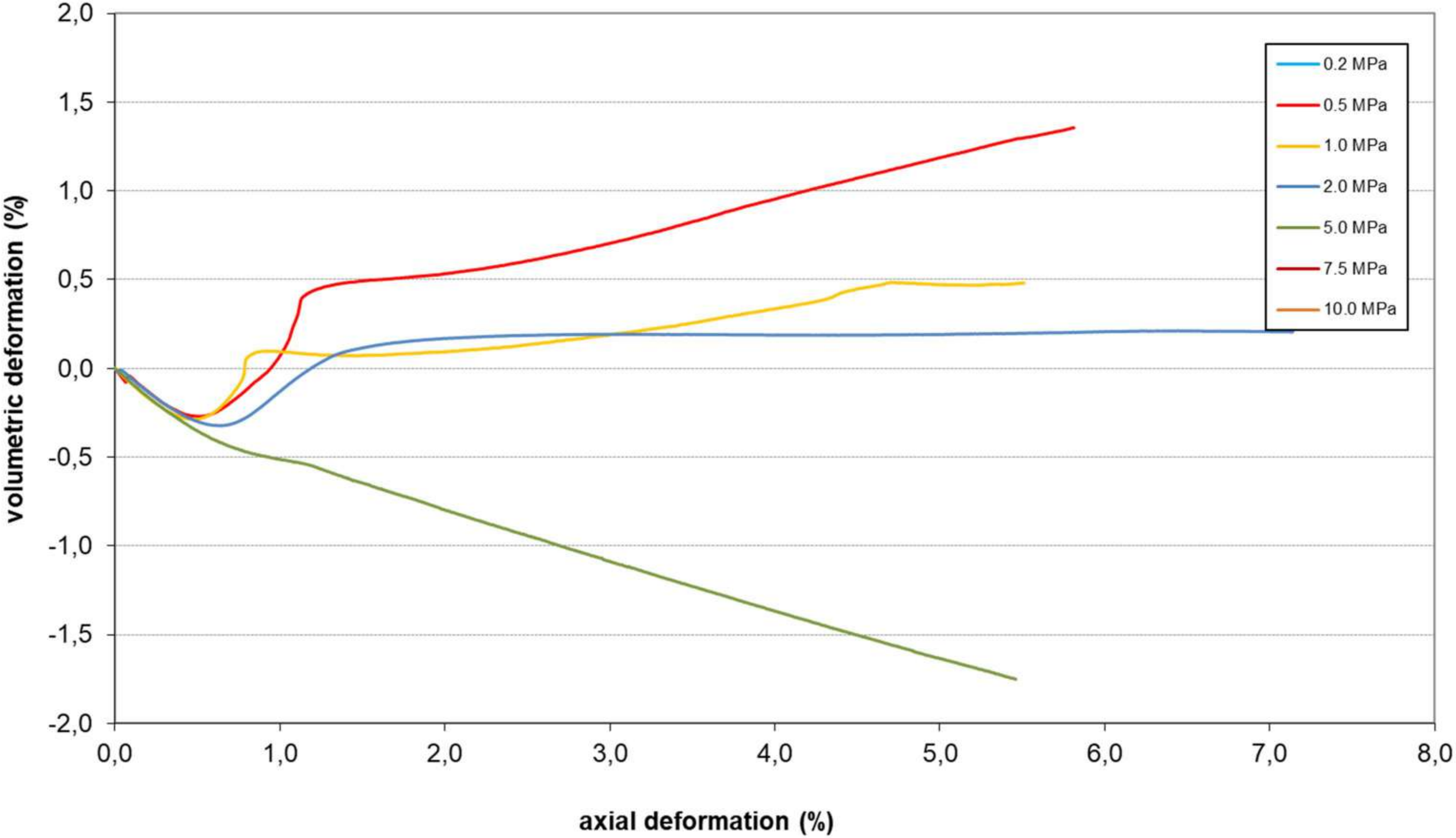
Triaxial strength tests (TC_nat)

Unit – PI (Poção Intercalado)

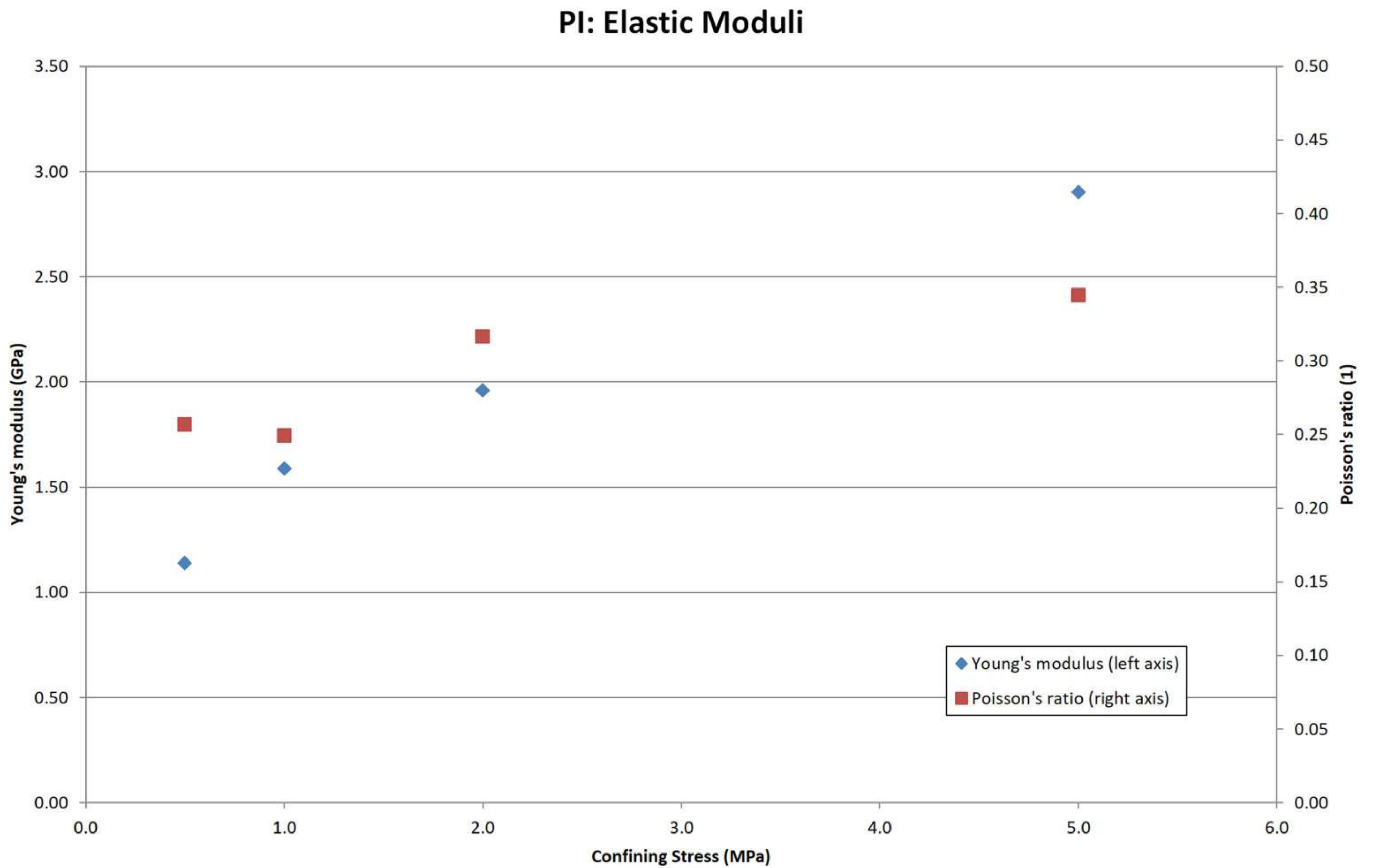
→ stress-strain curves of all tests

Appendix 103

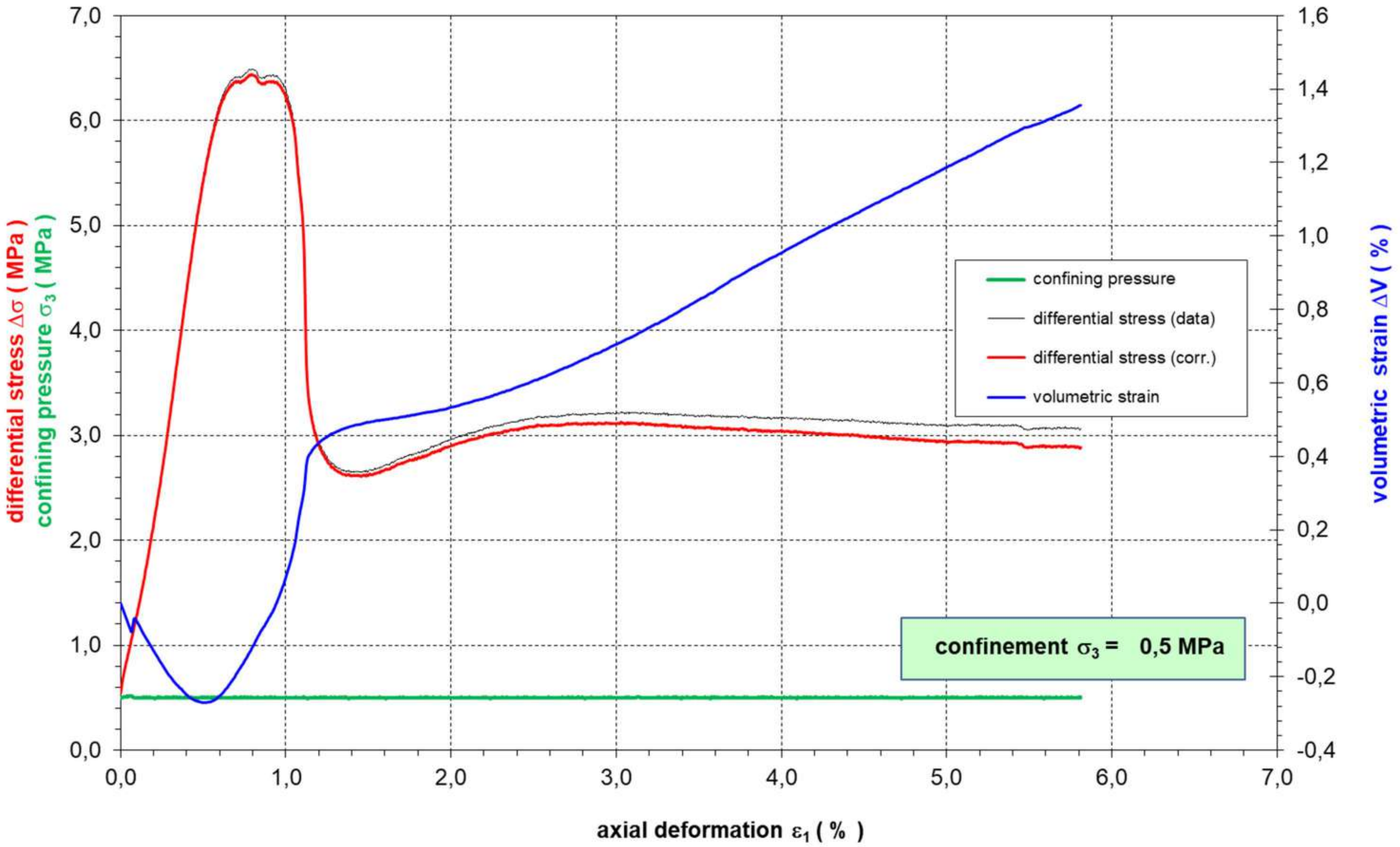
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
volumetric deformation (%)
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
axial deformation (%)
0.2 MPa
0.5 MPa
1.0 MPa
2.0 MPa
5.0 MPa
7.5 MPa
10.0 MPa



PI: Elastic Moduli
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Young's modulus (GPa)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Poisson's ratio (1)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Confining Stress (MPa)
Young's modulus (left axis)
Poisson's ratio (right axis)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

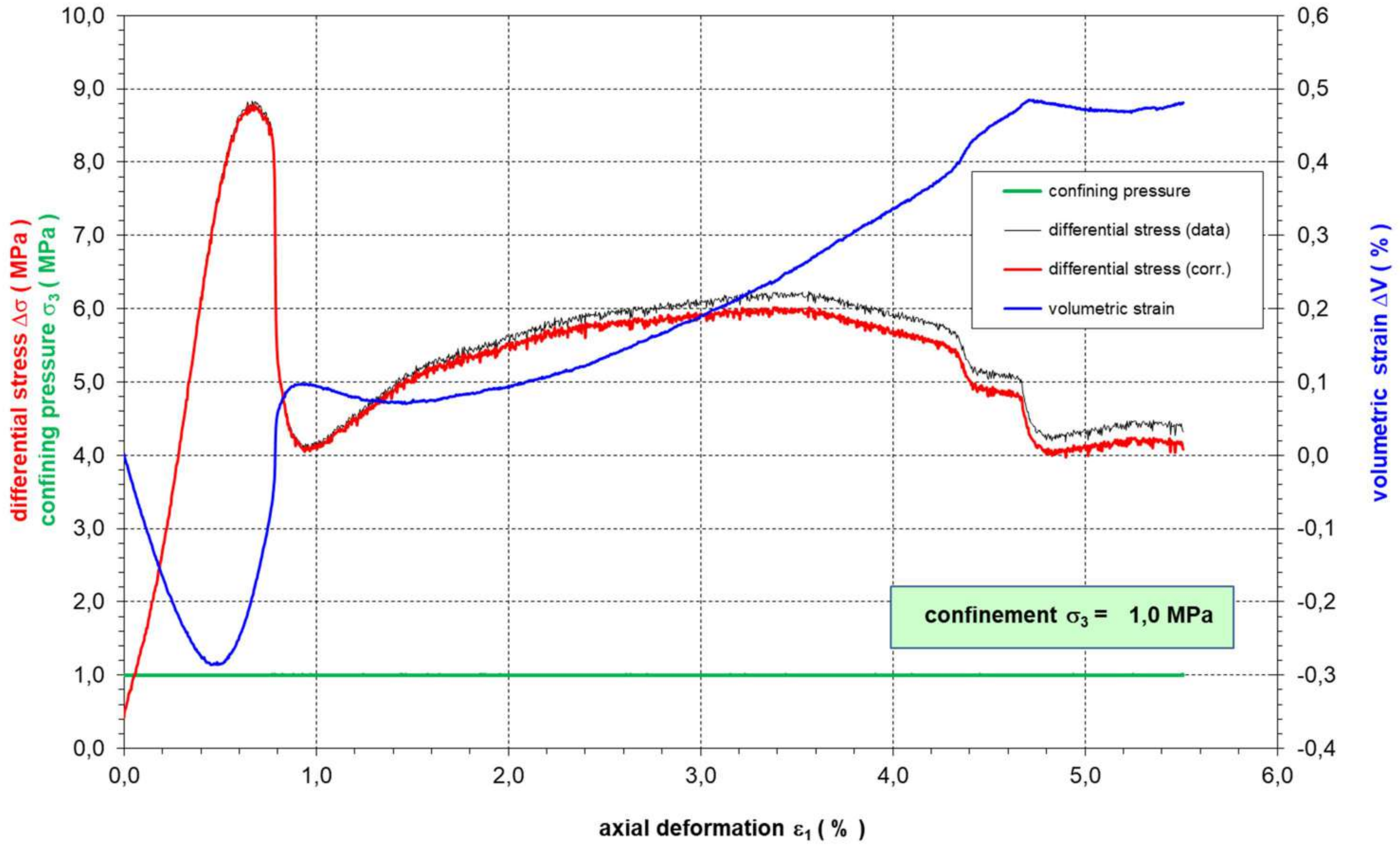
Triaxial strength test (TC_nat)

Unit – PI (Poção Intercalado)

→ stress-strain behavior; sample 743/PI001/TC_d1

Appendix 106

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

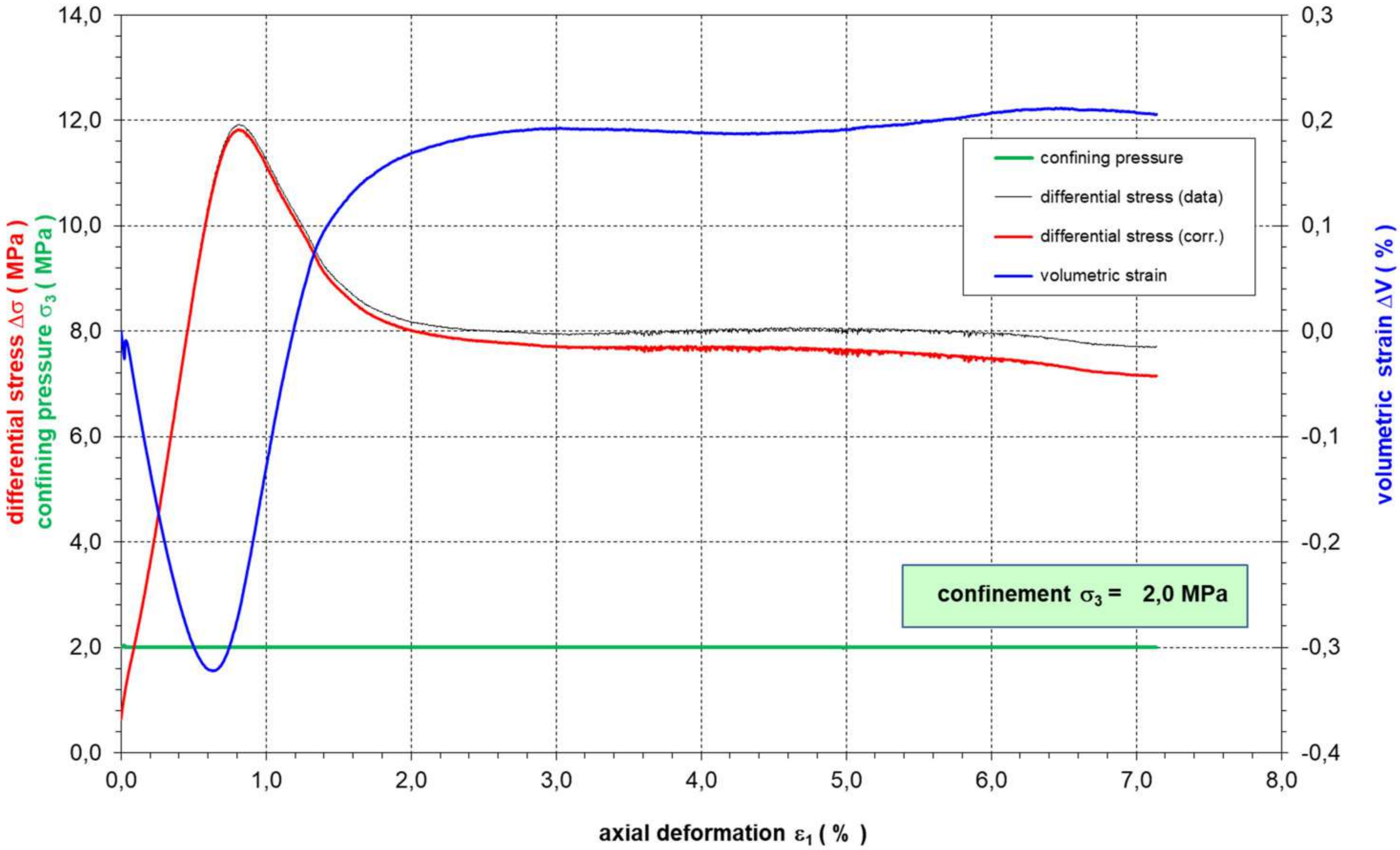
Triaxial strength test (TC_nat)

Unit – PI (Poção Intercalado)

→ stress-strain behavior; sample 743/PI002/TC_d2

Appendix 107

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

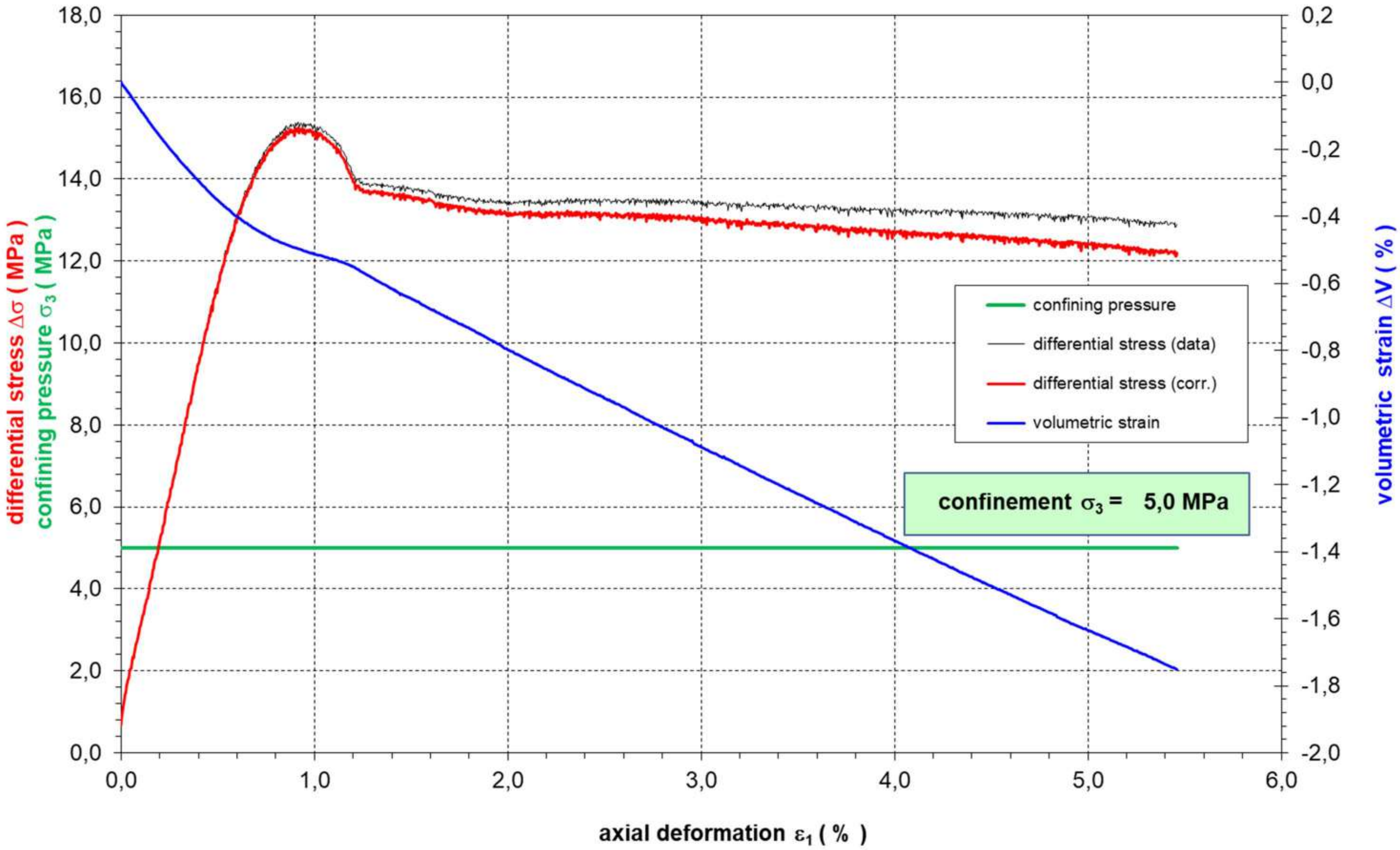
Triaxial strength test (TC_nat)

Unit – PI (Poção Intercalado)

→ stress-strain behavior; sample 743/PI003/TC_d3

Appendix 108

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – PI (Poção Intercalado)

→ stress-strain behavior; sample 743/PI006/TC_d4

Appendix 109

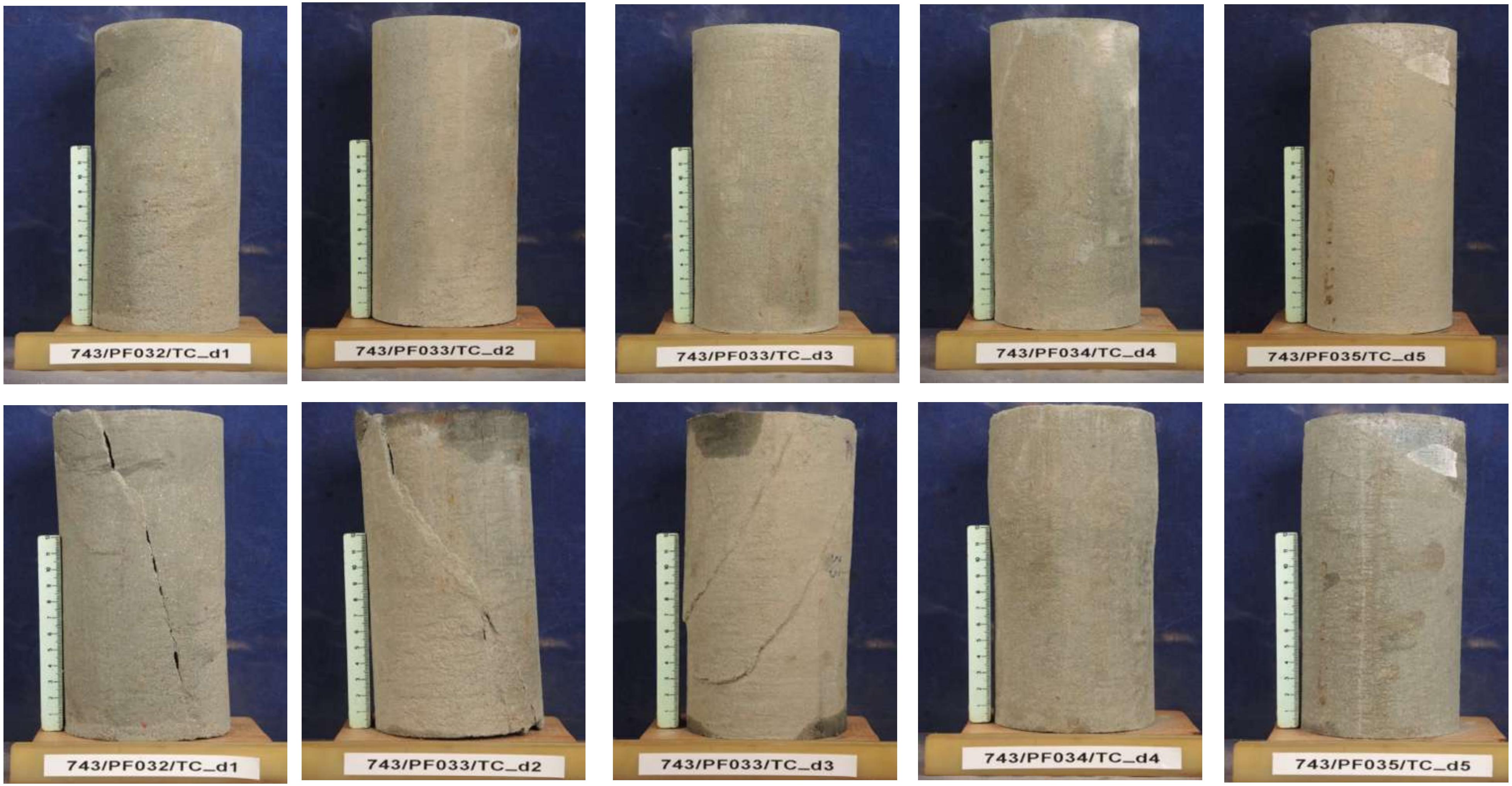
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	**9**	**9**		**6**	**6**	**3**	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/PF032/TC_d1	743/PF033/TC_d2	743/PF033/TC_d3	743/PF034/TC_d4	743/PF035/TC_d5
Rock Type / Unit	PF	PF	PF	PF	PF
Sample	PF_032	PF_033	PF_033	PF_034	PF_035
Depth (m)					
Length l (mm) =	200.703	199.640	200.123	199.288	199.655
Diameter d (mm) =	101.138	101.230	100.908	100.833	100.530
Ratio l_o/d_o =	1.98	1.97	1.98	1.98	1.99
Mass M (g) =	3099.90	2985.0	2962.0	2956.0	2981.9
Area A (cm^2) =	80.338	80.484	79.973	79.854	79.375
Volume V (cm^3) =	1612.40	1606.78	1600.44	1591.39	1584.75
Density ρ (g/cm^3) =	1.923	1.858	1.851	1.857	1.882
US L (h) – p	-	-	-	-	-
US Q1 (a/c) – p	40.24	-	-	-	39.65
US Q2 (b/d) - p	-	-	-	-	38.92
US L (h) - s	-	-	-	-	-
US L (h) - p(s)	-	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	2.51	-	-	-	2.54
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-	2.58
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-
E_d (GPa) =	-	-	-	-	-
K_d (GPa) =	-	-	-	-	-
G_d (GPa) =	-	-	-	-	-
ν_d =	-	-	-	-	-
	TC	TC	TC	TC	TC
Temp. (°C)	23	23	23	23	23
σ_3 (MPa) =	0.5	1.0	2.0	5.0	10.0
σ_{Dil} (MPa) =	10.2	9.6	14.3	13.5	13.5
ΔV_{Dil} (%) =	-0.25	-0.38	-0.34	-1.50	-0.27
ε_{Dil} (%) =	0.45	0.58	0.60	5.29	1.73
σ_{Fail} (MPa) =	10.9	9.9	14.3	16.0	16.0
ΔV_{Fail} (%) =	-0.23	-0.38	-0.34	-0.47	0.52
ε_{Fail} (%) =	0.53	0.62	0.62	0.82	6.07
σ_{1Fail} (MPa) =	11.38	10.86	16.33	21.02	26.01
α (°) =	65	65	65	65	65
σ_n (MPa) =	2.44	2.76	4.56	7.86	12.86
τ (MPa) =	4.17	3.78	5.49	6.13	6.13
ϕ=			13.0		
C=			4.5		

BEFORE:

AFTER:



σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 2.0 MPa | σ_3 = 5.0 MPa | σ_3 = 10.0 MPa

IfG INSTITUT FÜR GEBIRGSMECHANIK GMBH

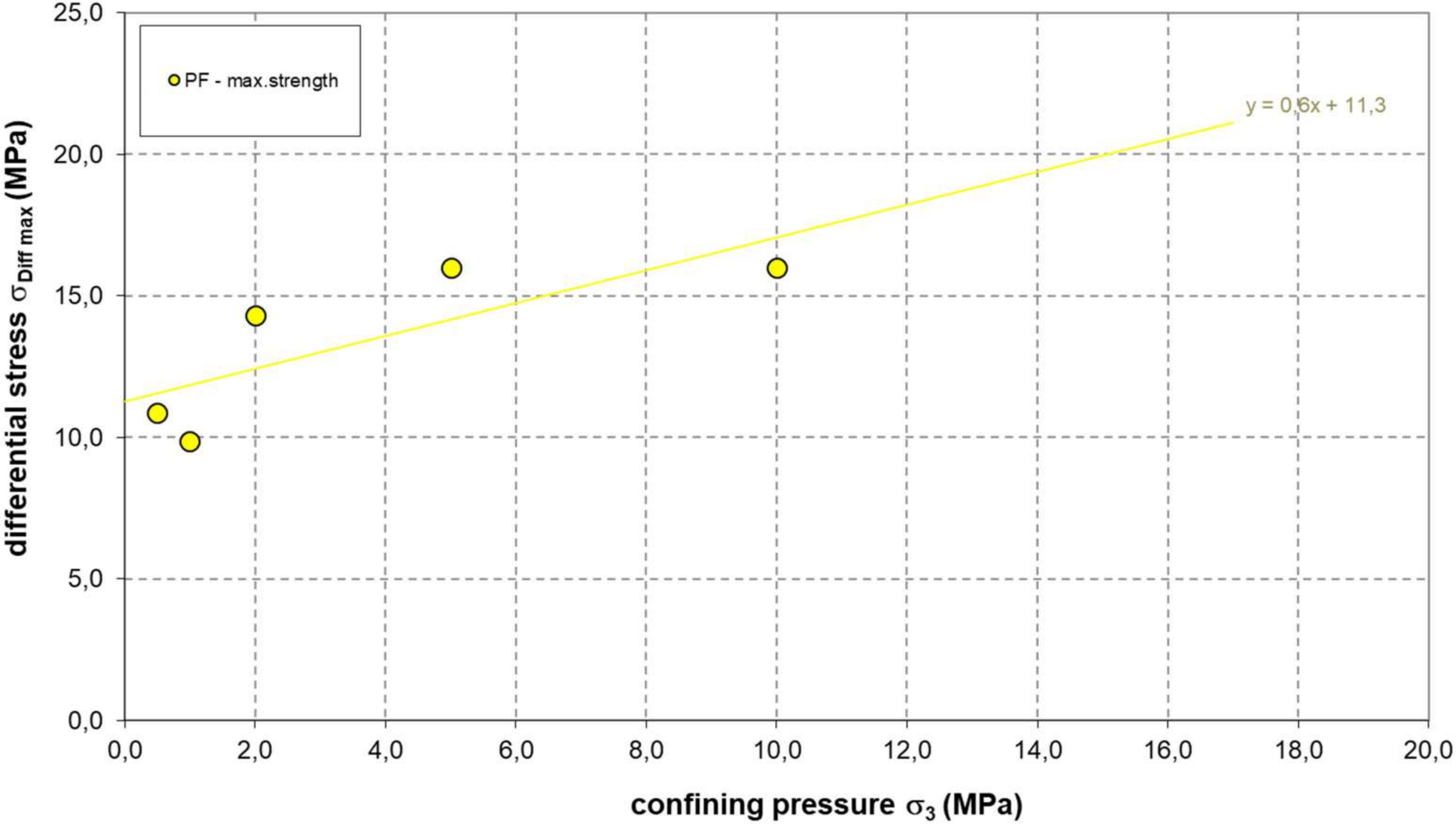
Samples for triaxial strength tests (TC_nat)

Unit – PF (Poção Folhelho)

→ photo-documentation before and after the test

Appendix 112

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

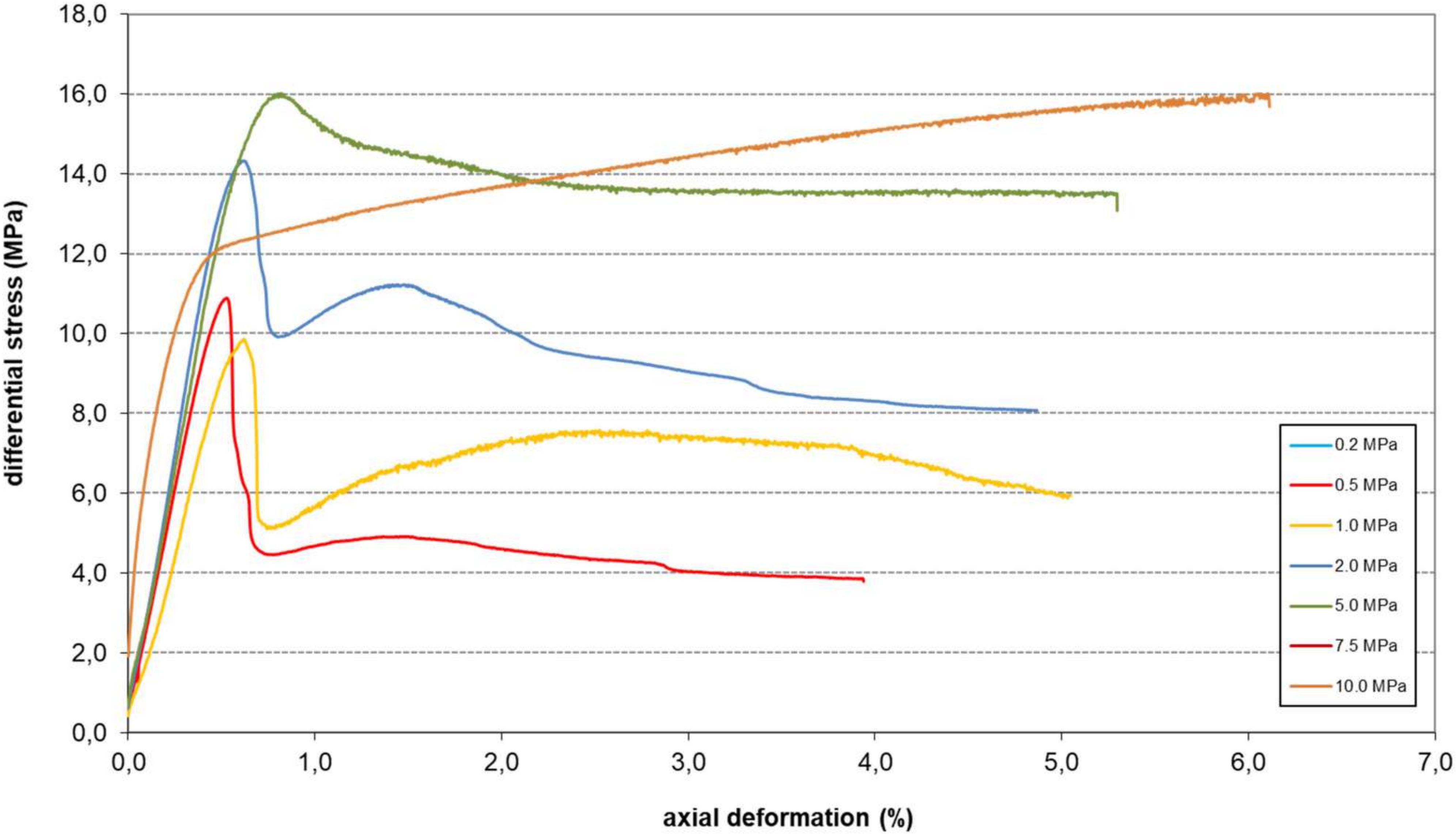
Triaxial strength tests (TC_nat)

Unit – PF (Poção Folhelho)

→ maximum strength values dependent on the radial stress

Appendix 113

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

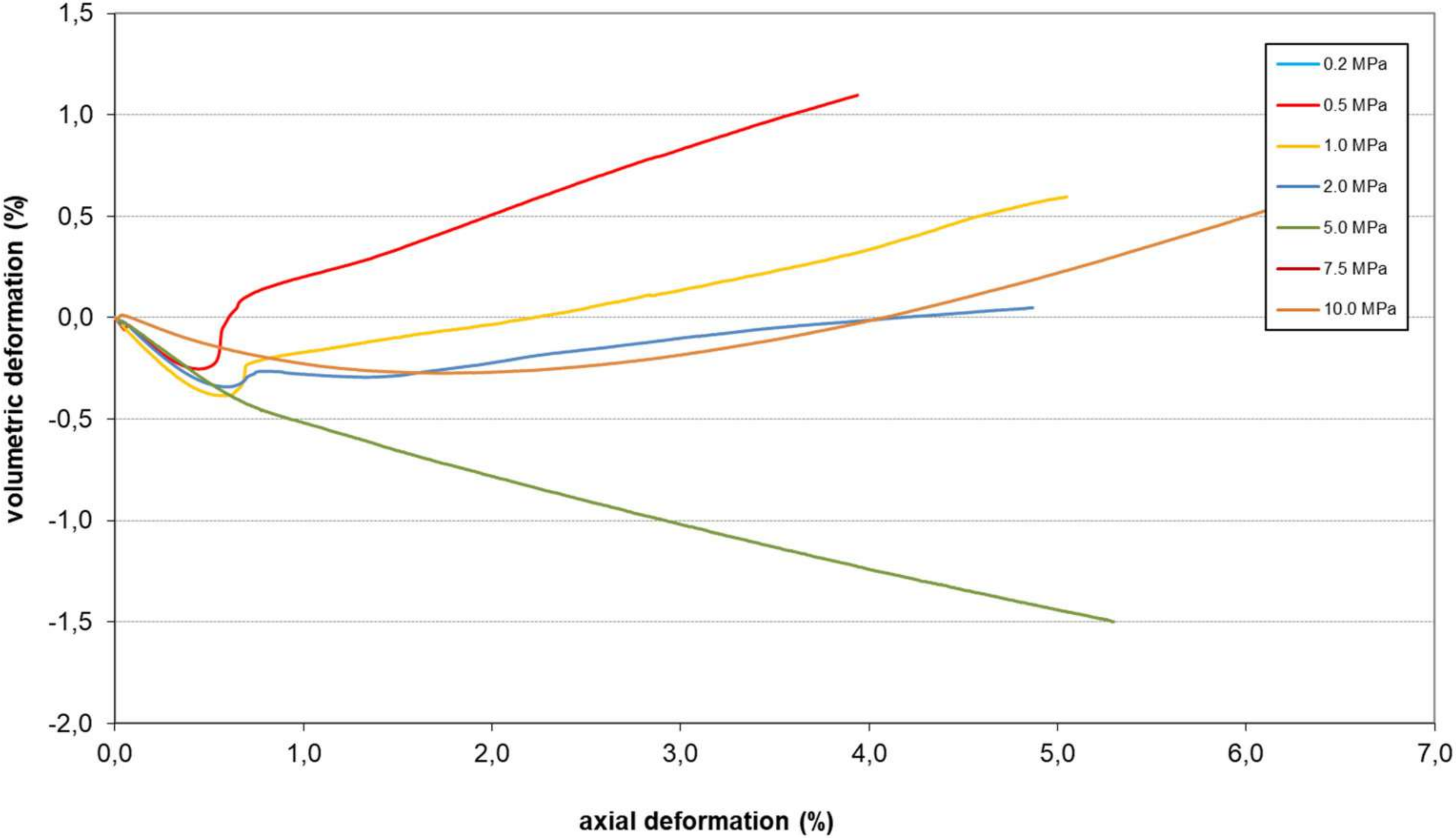
Triaxial strength tests (TC_nat)

Unit – PF (Poção Folhelho)

→ stress-strain curves of all tests

Appendix 114

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

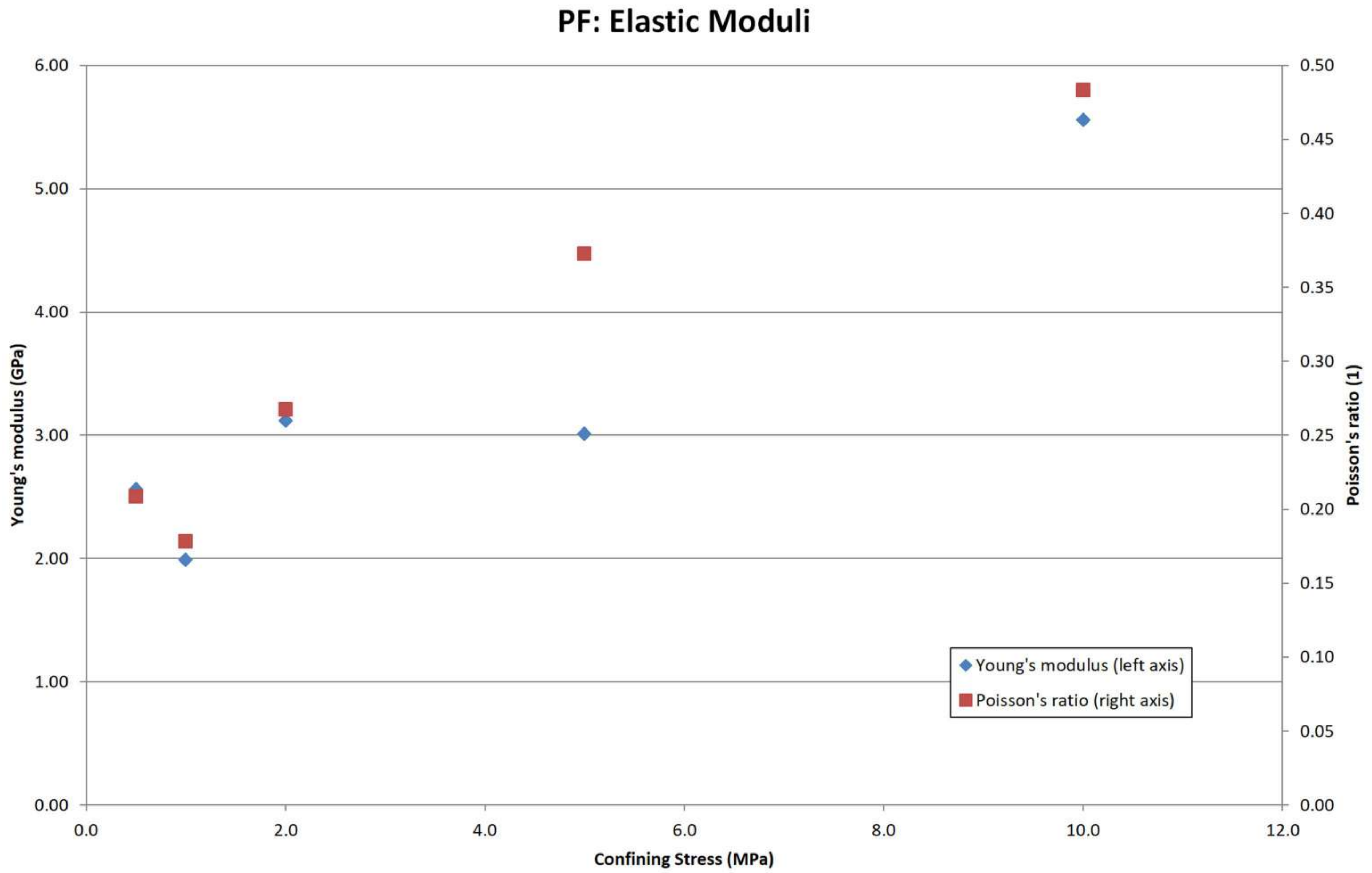
Triaxial strength tests (TC_nat)

Unit – PF (Poção Folhelho)

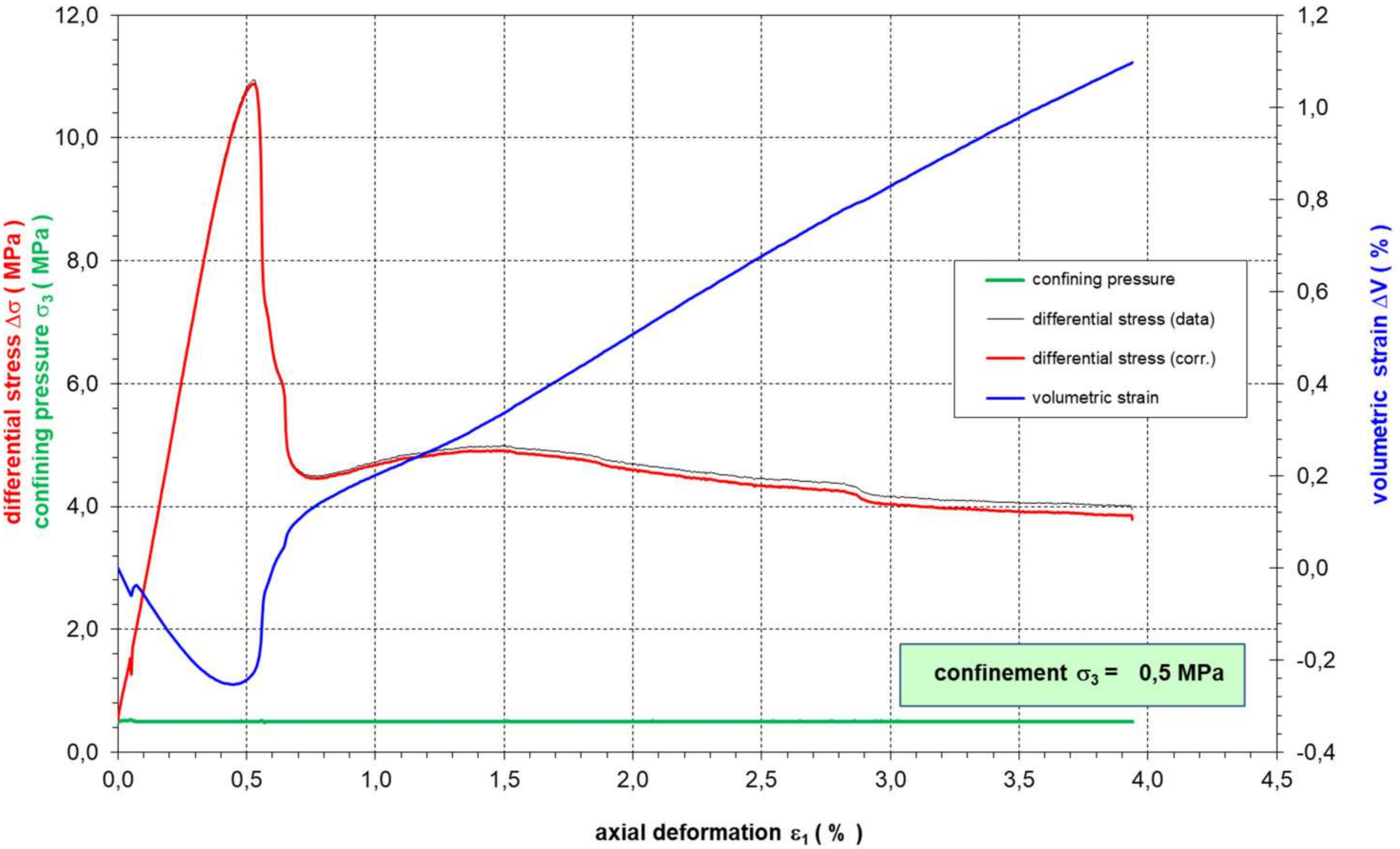
→ volumetric strain vs. axial deformation; dilatancy curves

Appendix 115

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



PF: Elastic Moduli
Young's modulus (GPa)
Poisson's ratio (1)
Confining Stress (MPa)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Young's modulus (left axis)
Poisson's ratio (right axis)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

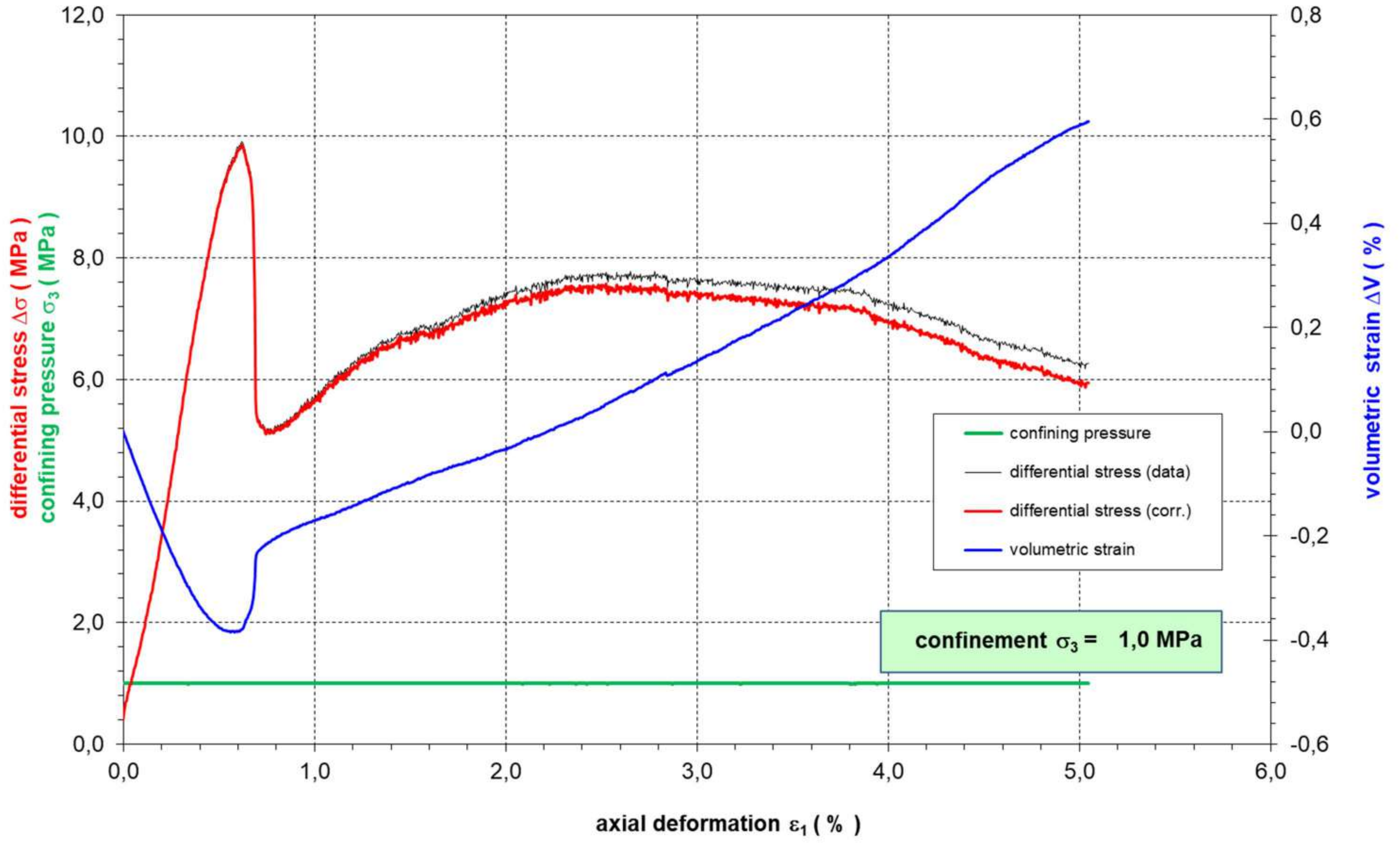
Triaxial strength test (TC_nat)

Unit – PF (Poção Folhelho)

→ stress-strain behavior; sample 743/PF035/TC_d1

Appendix 117

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

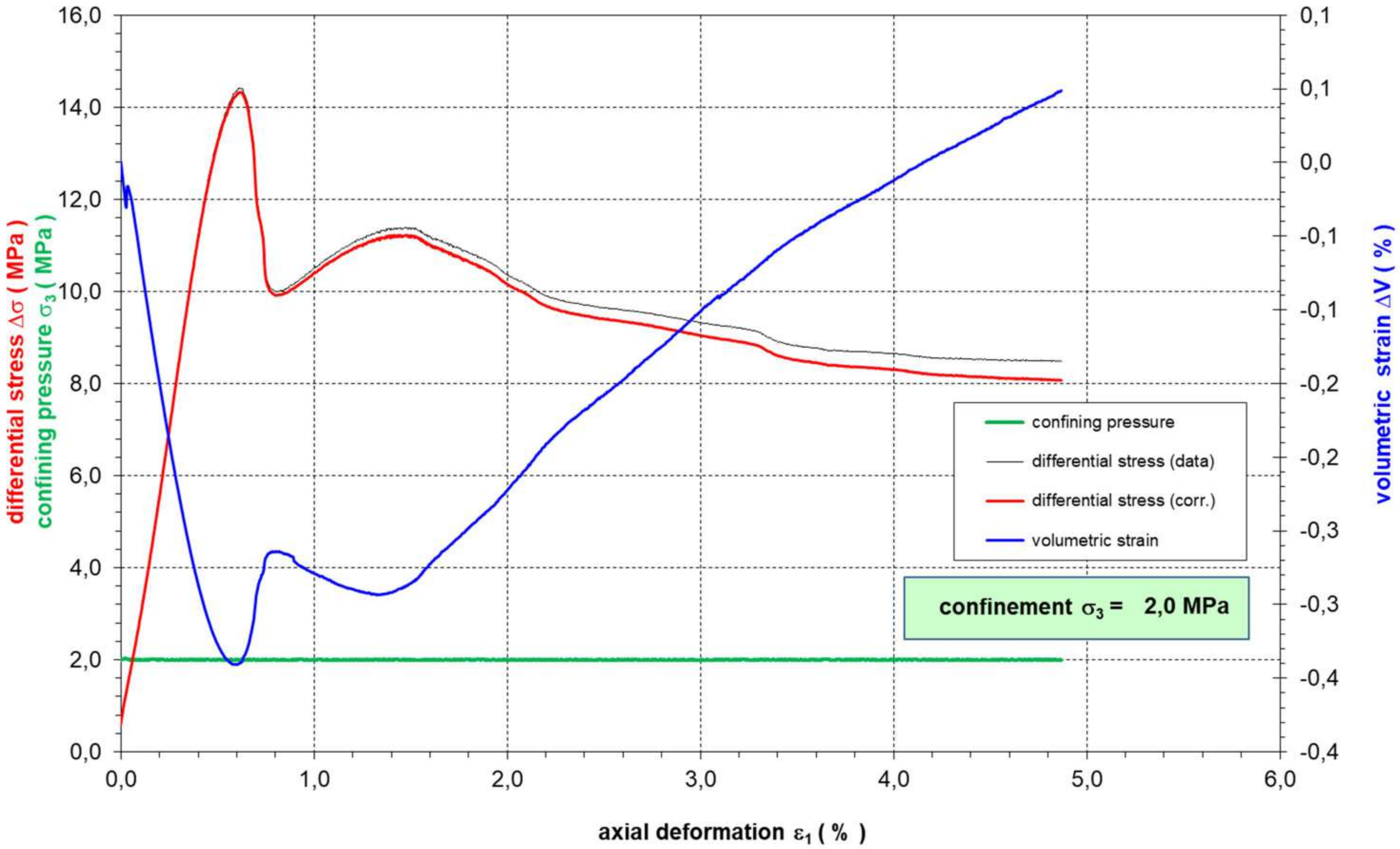
Triaxial strength test (TC_nat)

Unit – PF (Poção Folhelho)

→ stress-strain behavior; sample 743/PF033/TC_d2

Appendix 118

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

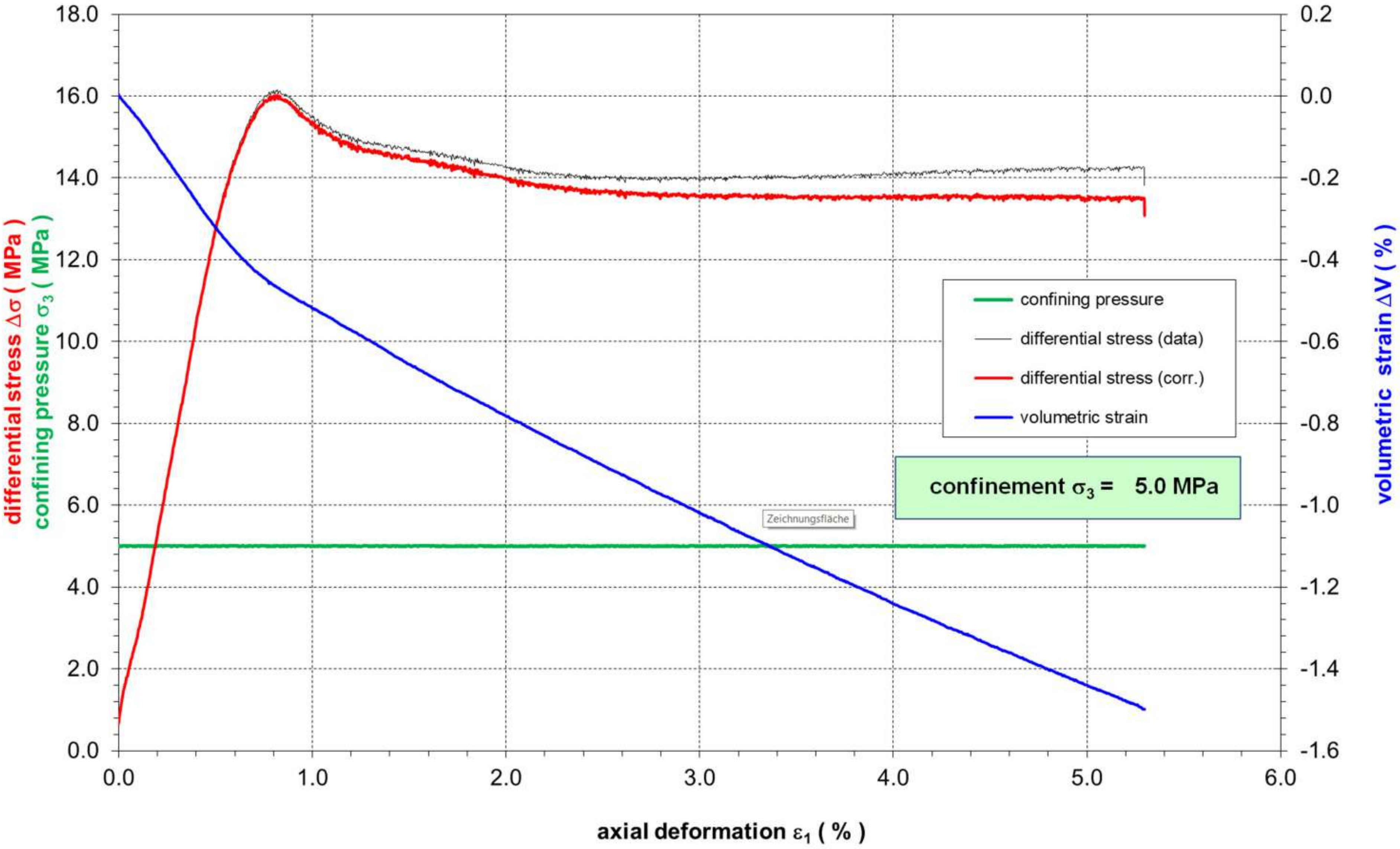
Triaxial strength test (TC_nat)

Unit – PF (Poção Folhelho)

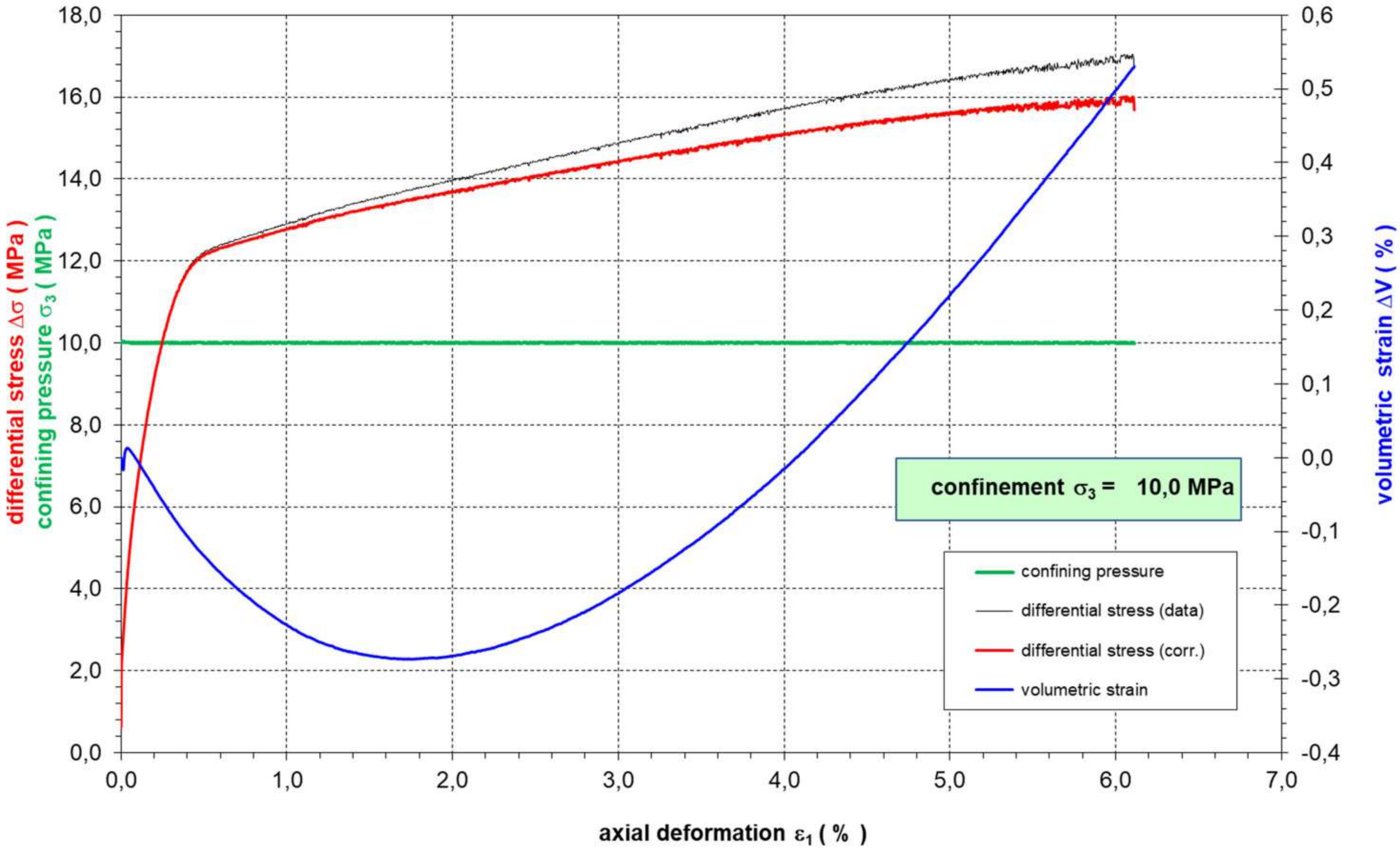
→ stress-strain behavior; sample 743/PF033/TC_d3

Appendix 119

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
0.0
1.0
2.0
3.0
4.0
5.0
6.0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 5.0 MPa
Zeichnungsfläche



INSTITUT FÜR GEBIRGSMECHANIK GMBH

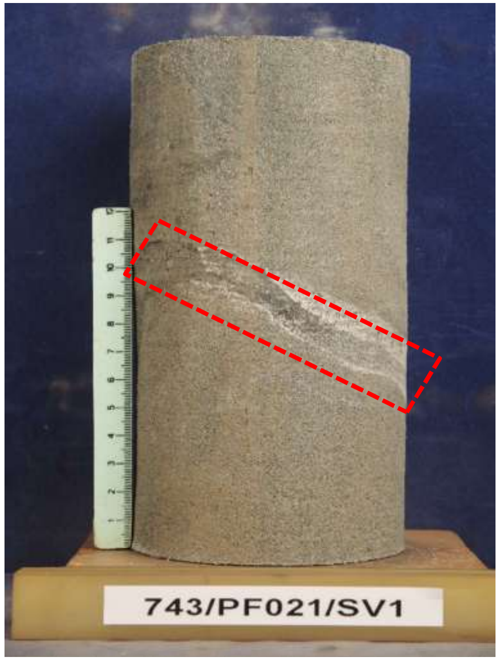
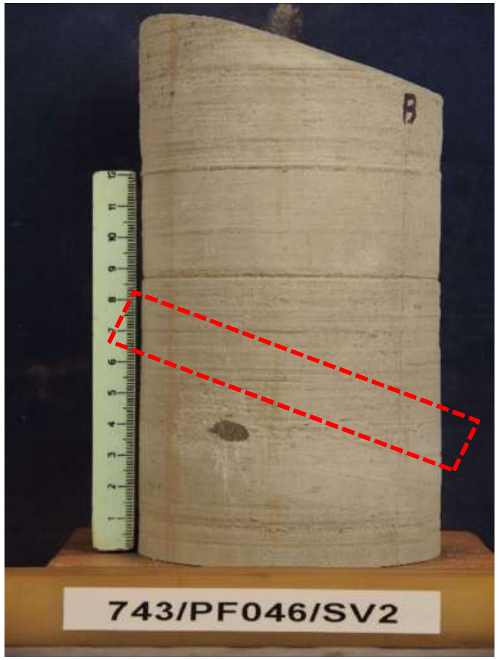
Triaxial strength test (TC_nat)

Unit – PF (Poção Folhelho)

→ stress-strain behavior; sample 743/PF033/TC_d5

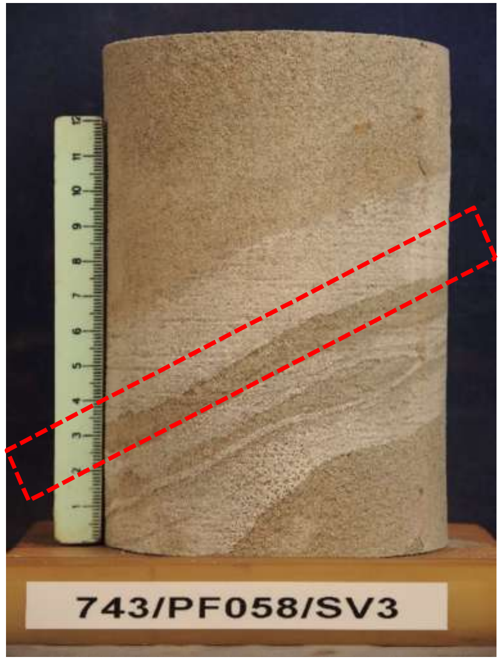
Appendix 121

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

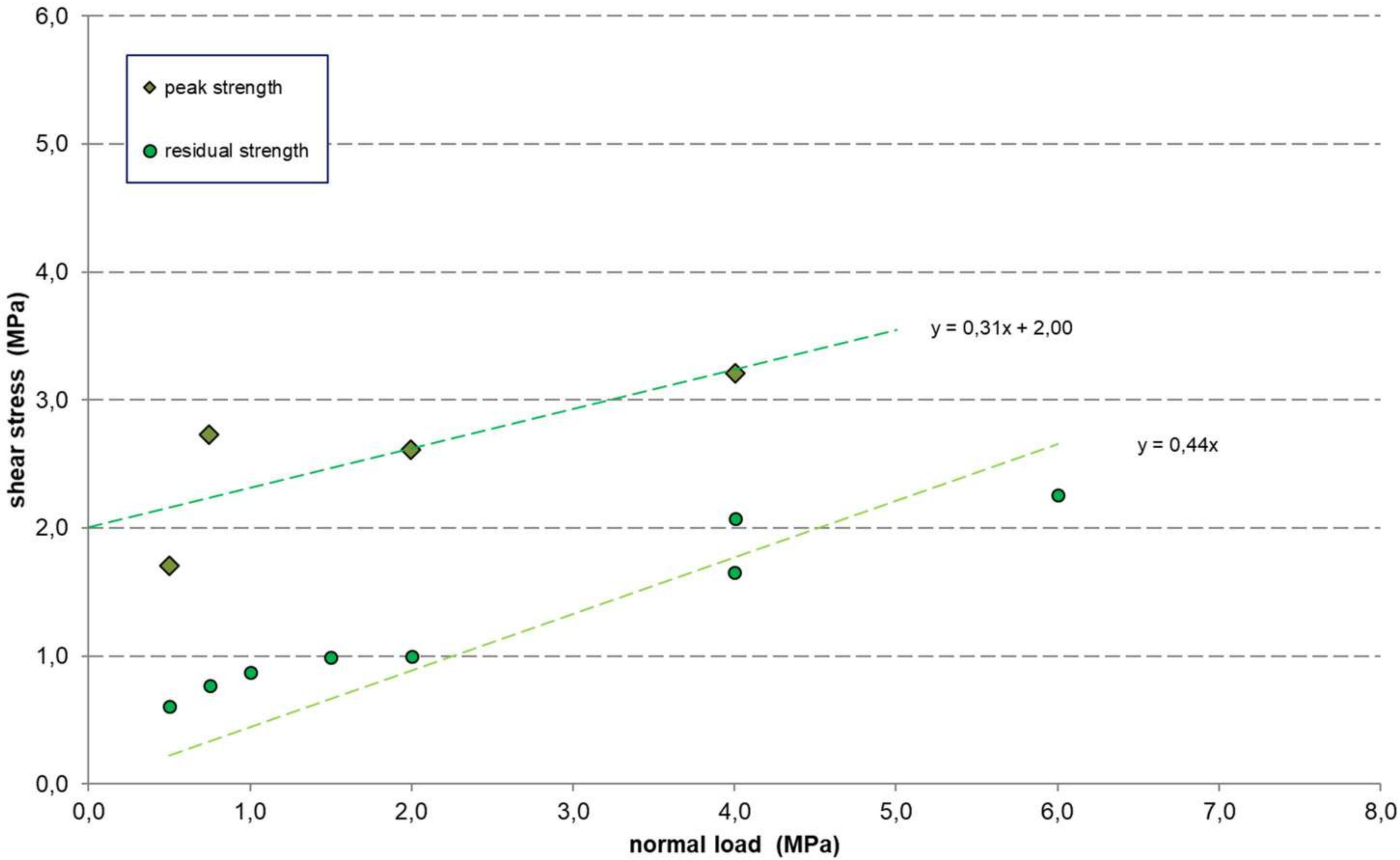

743/PF021/SV1

743/PF046/SV2

743/PF021/SV1

43/PF046/SV2


743/PF058/SV3

743/PF056/SV4



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

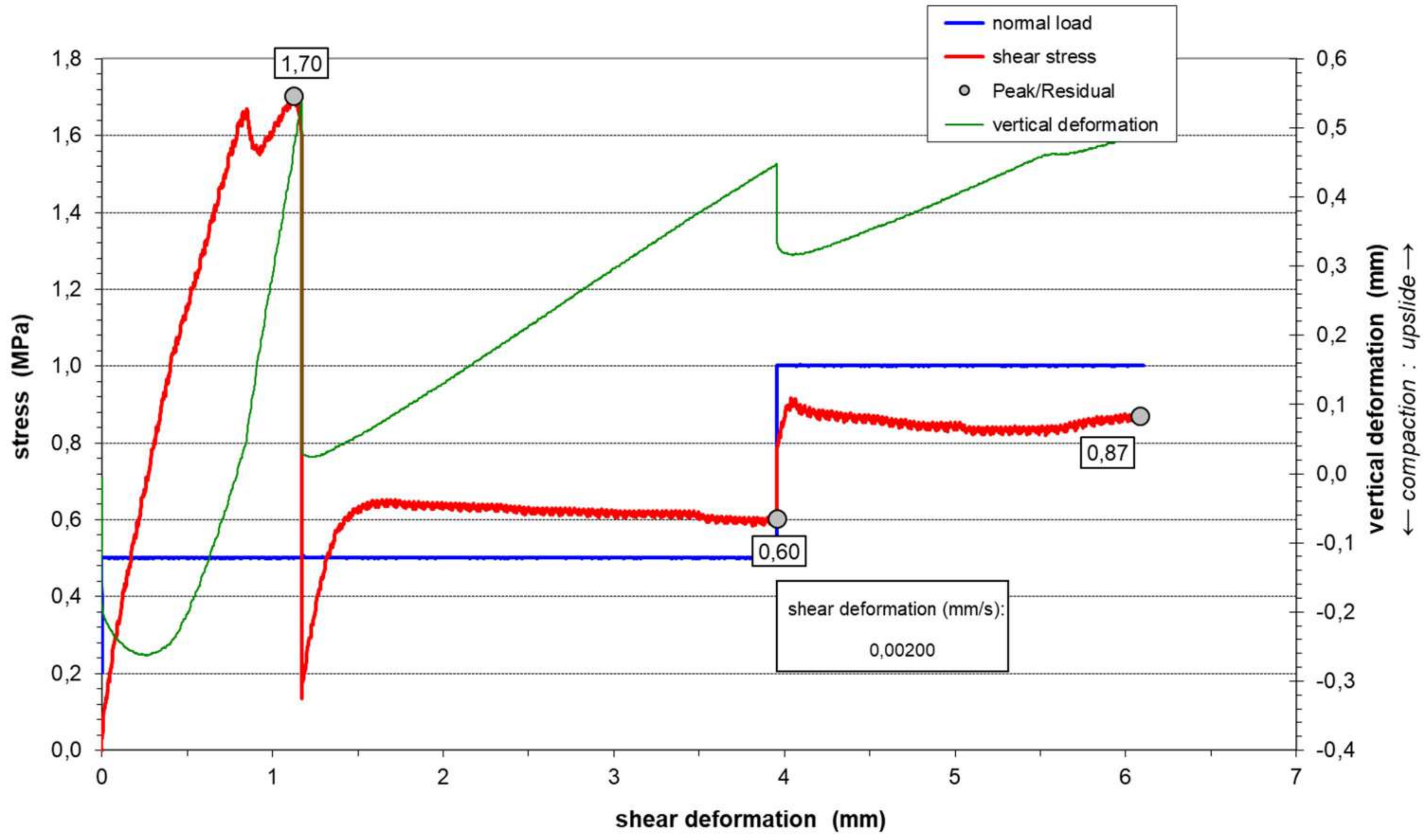
Direct shear tests (DST)

Unit – PF (Poção Folhelho)

→ peak and residual strength values

Appendix 124

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

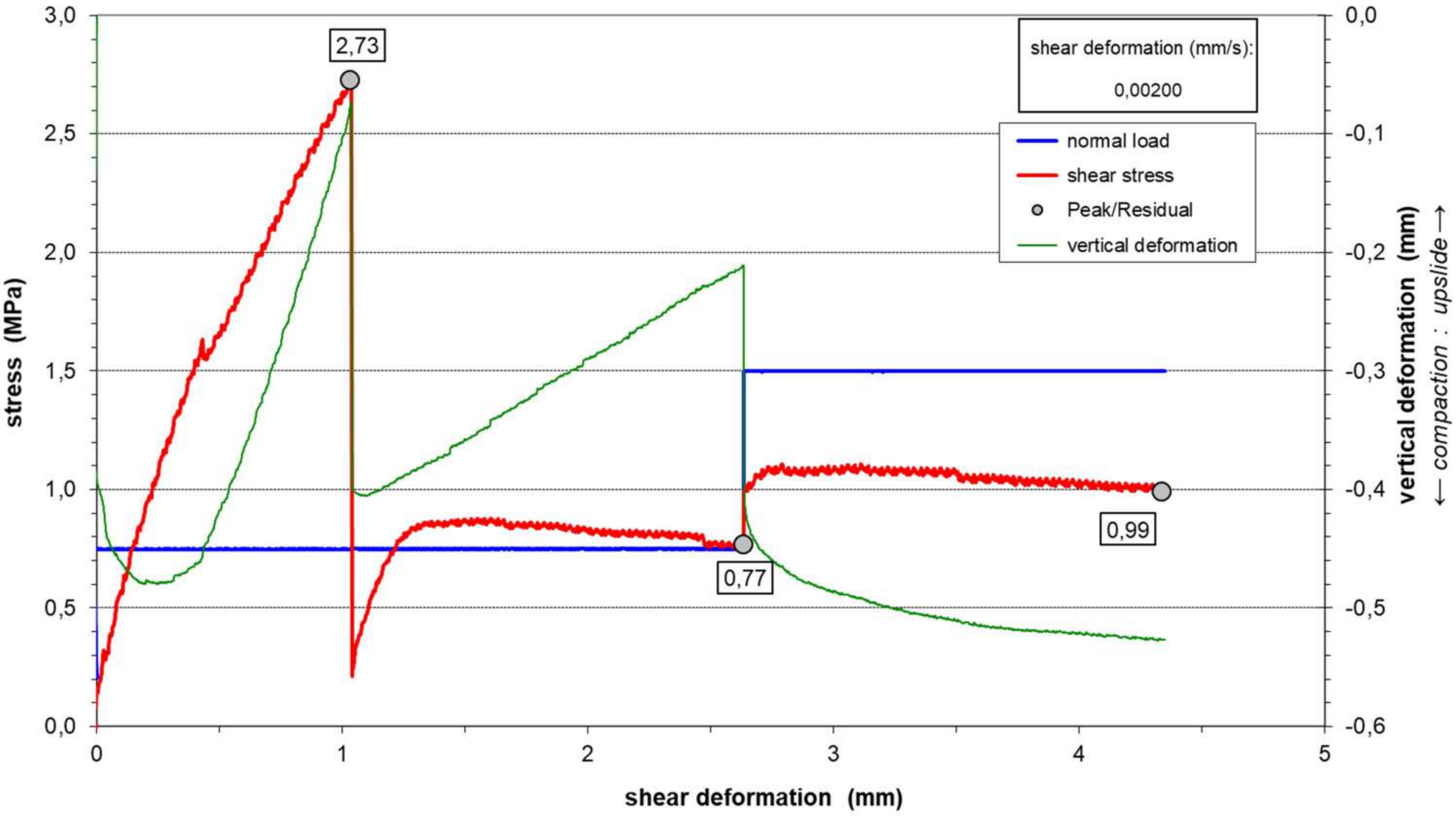
Direct shear test (DST)

Unit – PF (Poção Folhelho)

743/PF021/SV1

Appendix 125

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

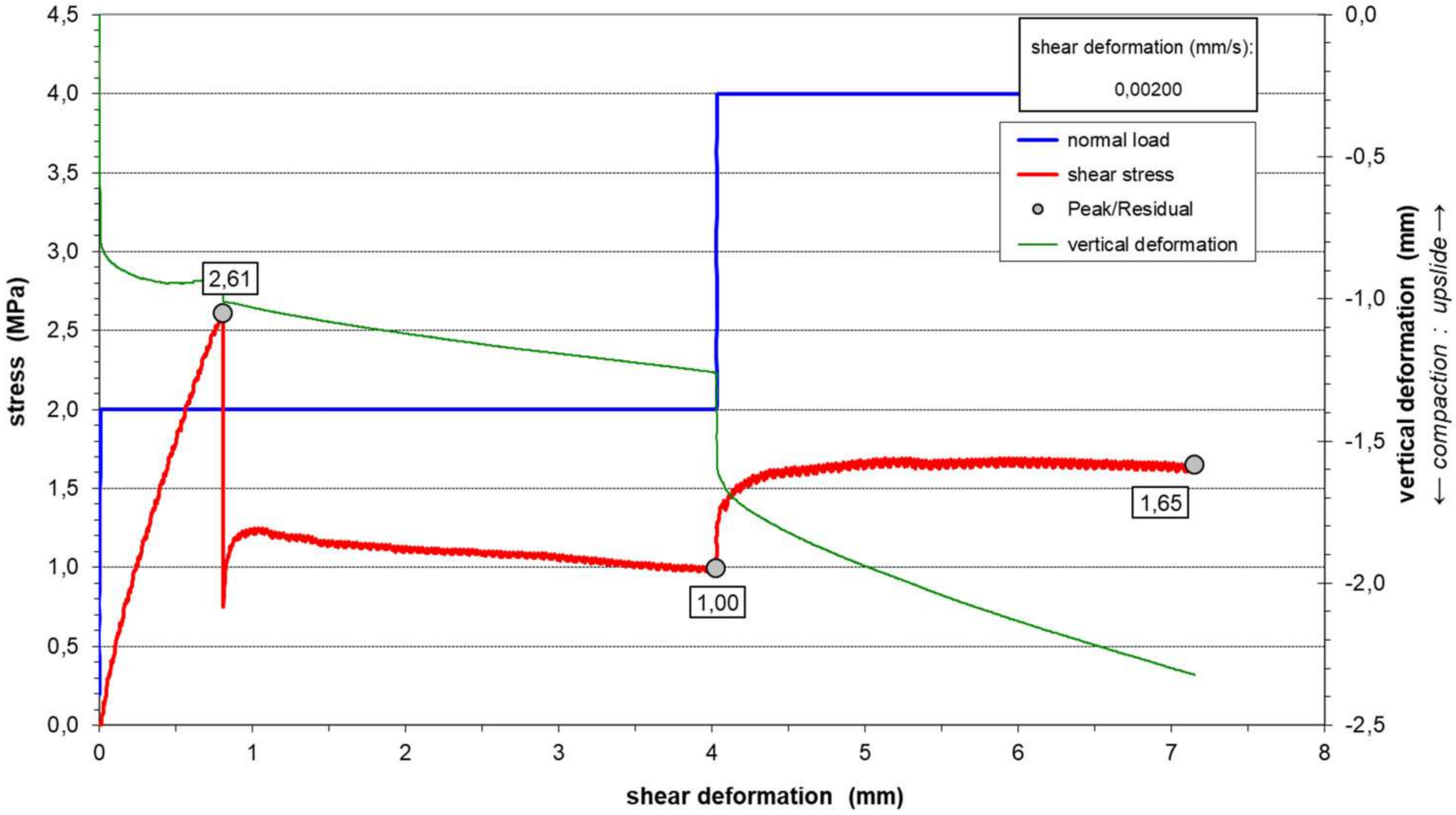
Direct shear test (DST)

Unit – PF (Poção Folhelho)

743/PF046/SV2

Appendix 126

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

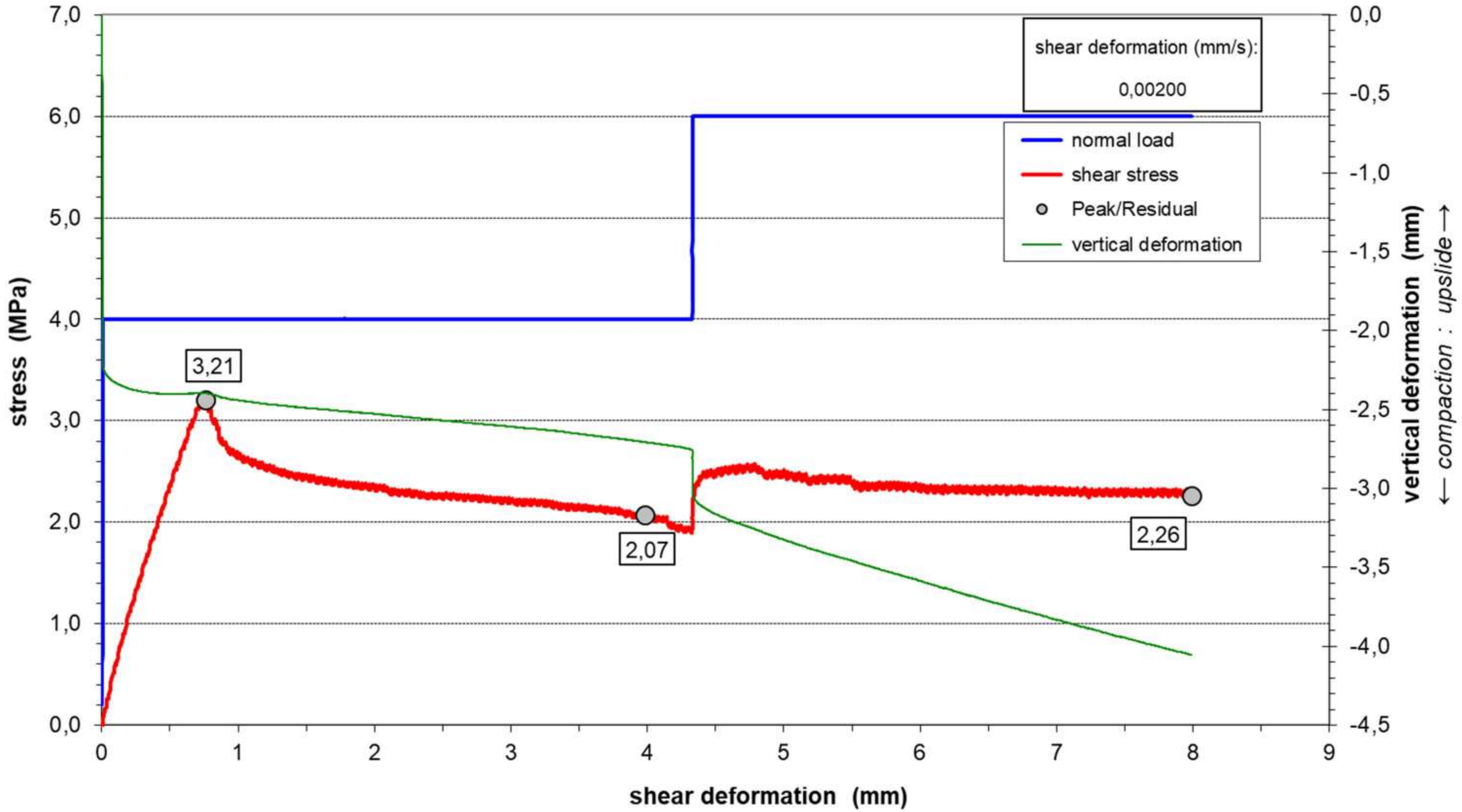
Direct shear test (DST)

Unit – PF (Poção Folhelho)

743/PF085/SV3

Appendix 127

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Direct shear test (DST)
Unit – PF (Poção Folhelho)
743/PF056/SV4

Appendix 128

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	**9**	**9**	**5**	**6**	**6**	**6**	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/005/TC_d1	743/027/TC_d2	743/046/TC_d3	743/054/TC_d4	743/116/TC_d5	743/103/TC_d6	743/112/TC_d7	743/014/TC_d8	743/082/TC_d9
Rock Type / Unit Sample	TMS TMS-005	TMS TMS-027	TMS TMS-046	TMS TMS-054	TMS TMS-116	TMS TMS-103	TMS TMS-112	TMS TMS-014	TMS TMS-082
Depth (m)									
Length l (mm) =	199.592	199.925	200.715	199.748	199.145	201.020	198.633	200.390	195.568
Diameter d (mm) =	100.520	100.460	100.067	99.992	99.227	101.135	99.123	100.315	101.01
Ratio l_o/d_o =	1.99	1.99	2.01	2.00	2.01	1.99	2.00	2.00	1.94
Mass M (g) =	3727.20	3847.2	3720.1	3668.9	3353.4	3741.8	3227.4	3809.9	3388.1
Area A (cm^2) =	79.359	79.264	78.645	78.527	77.330	80.333	77.168	79.035	80.134
Volume V (cm^3) =	1583.94	1584.69	1578.53	1568.57	1539.99	1614.85	1532.82	1583.79	1567.17
Density ρ (g/cm^3) =	2.353	2.428	2.357	2.339	2.178	2.317	2.106	2.406	2.162
US L (h) - p	-	-	-	-	-	-	-	-	-
US Q1 (a/c) - p	30.73	28.44	30.14	36.37	-	31.74	-	25.35	-
US Q2 (b/d) – p	30.59	25.74	29.53	27.07	-	-	-	24.32	-
US L (h) - s	-	-	-	-	-	-	-	-	-
US L (h) - p(s)	-	-	-	-	-	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	3.27	3.53	3.32	2.75	-	3.19	-	3.96	-
$V_{p\text{-radial: b-d}}$ (km/s) =	3.29	3.90	3.39	3.69	-	-	-	4.12	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-	-	-	-	-
E_d (GPa) =	-	-	-	-	-	-	-	-	-
K_d (GPa) =	-	-	-	-	-	-	-	-	-
G_d (GPa) =	-	-	-	-	-	-	-	-	-
ν_d =	-	-	-	-	-	-	-	-	-
	TC	**TC**	**TC**	**TC**	**TC**	**TC**	**TC**	**TC**	**TC**
Temp. (°C)	**23**	**23**	**23**	**23**	**23**	**23**	**23**	**23**	**23**
σ_3 (MPa) =	0.2	0.5	1.0	3.0	5.0	10.0	16.0	7.5	12.5
σ_{Dil} (MPa) =	20.2	11.7	18.9	20.4	24.2	23.8	23.8	61.4	31.5
ΔV_{Dil} (%) =	-0.52	-0.35	-0.48	-0.34	-0.39	-0.51	-1.45	-0.35	-0.75
ε_{Dil} (%) =	0.65	0.57	0.76	0.71	0.83	0.81	10.94	0.59	1.43
σ_{Fail} (MPa) =	20.2	12.5	19.1	20.5	27.1	23.8	27.5	64.1	32.4
ΔV_{Fail} (%) =	-0.52	-0.33	-0.48	-0.34	-0.31	-0.51	-1.16	-0.33	-0.74
ε_{Fail} (%) =	0.65	0.67	0.77	0.72	1.23	0.81	2.96	0.69	1.31
σ_{1Fail} (MPa) =	20.37	12.97	20.14	23.55	32.13	33.75	43.54	71.63	44.91
α (°) =	65	65	65	65	65	65	65	65	65
σ_n (MPa) =	3.80	2.73	4.42	6.67	9.85	14.24	20.92	18.95	18.29
τ (MPa) =	7.73	4.78	7.33	7.87	10.39	9.10	10.55	24.56	12.41
ϕ=					**19.5**				
C=					**7.5**				

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

Unit – TMS (Tabuleiro)

→ petrophysical parameters and stress-strain-values

Appendix 130

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:

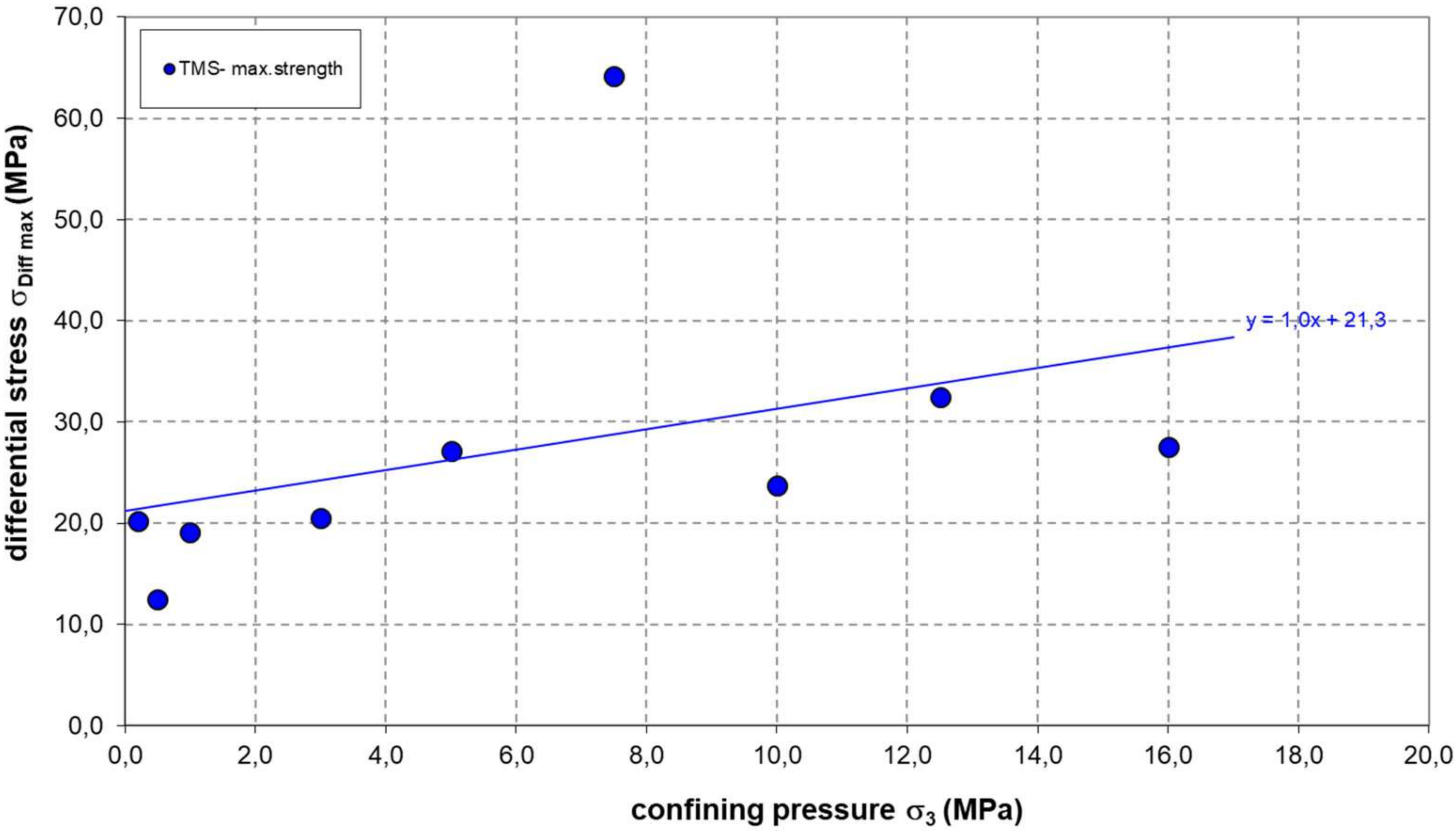
AFTER:

σ_3 = 0.2 MPa | σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 3.0 MPa | σ_3 = 5.0 MPa

BEFORE:

AFTER:

σ_3 = 10.0 MPa	σ_3 = 16.0 MPa	σ_3 = 7.5 MPa	σ_3 = 12.5 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

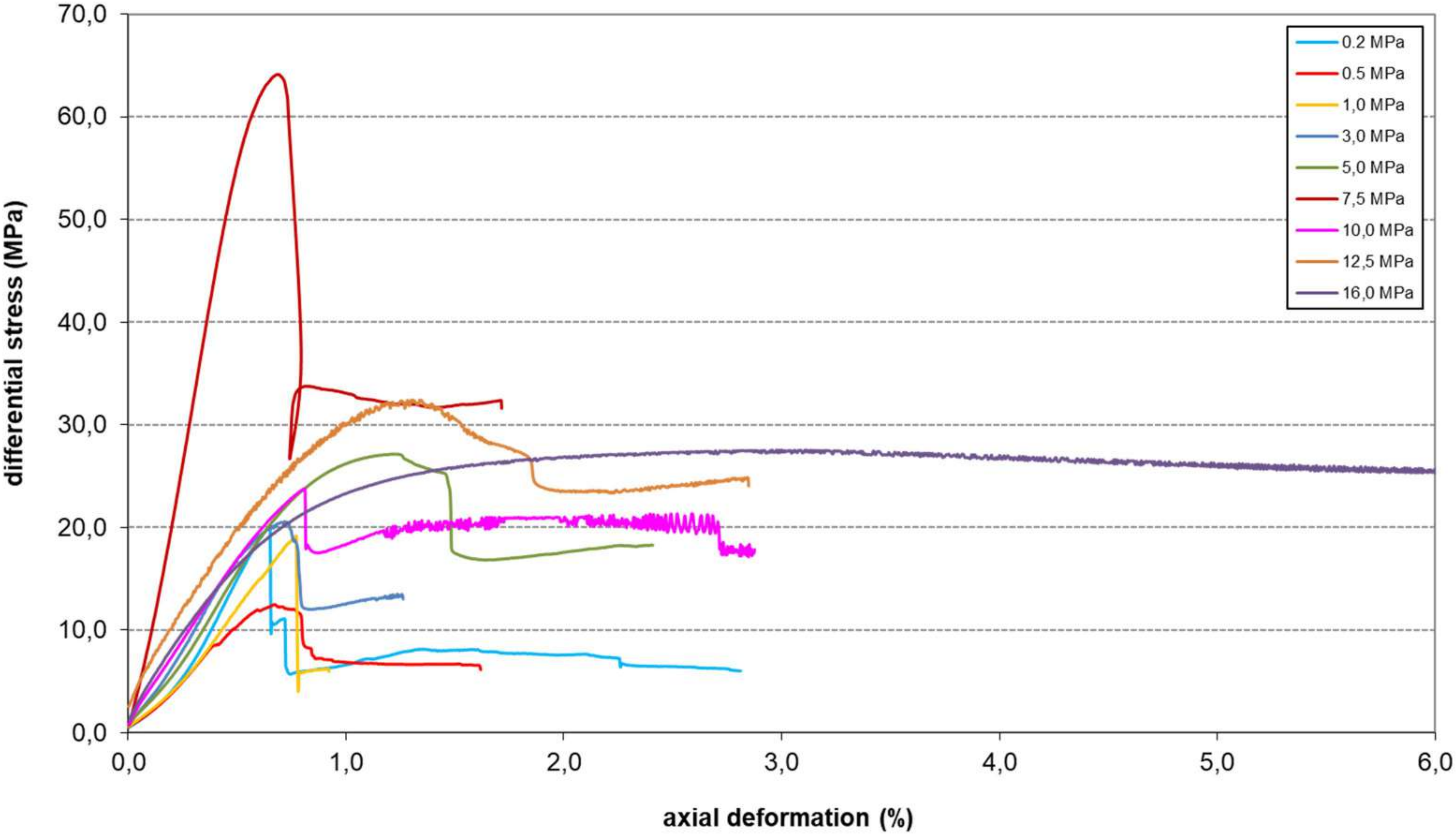
Triaxial strength tests (TC_nat)

Unit – TMS (Tabuleiro)

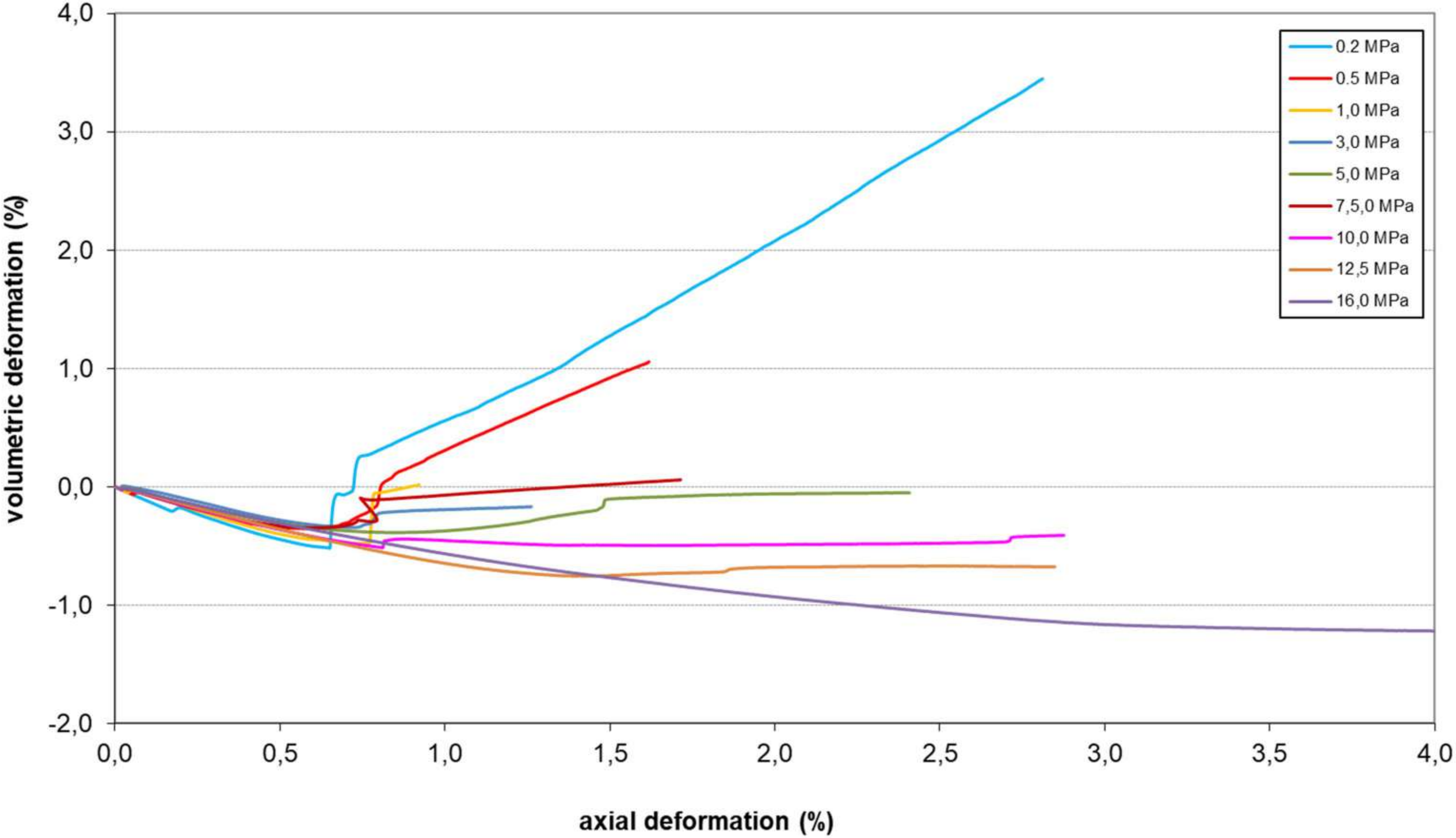
→ maximum strength values dependent on the radial stress

Appendix 133

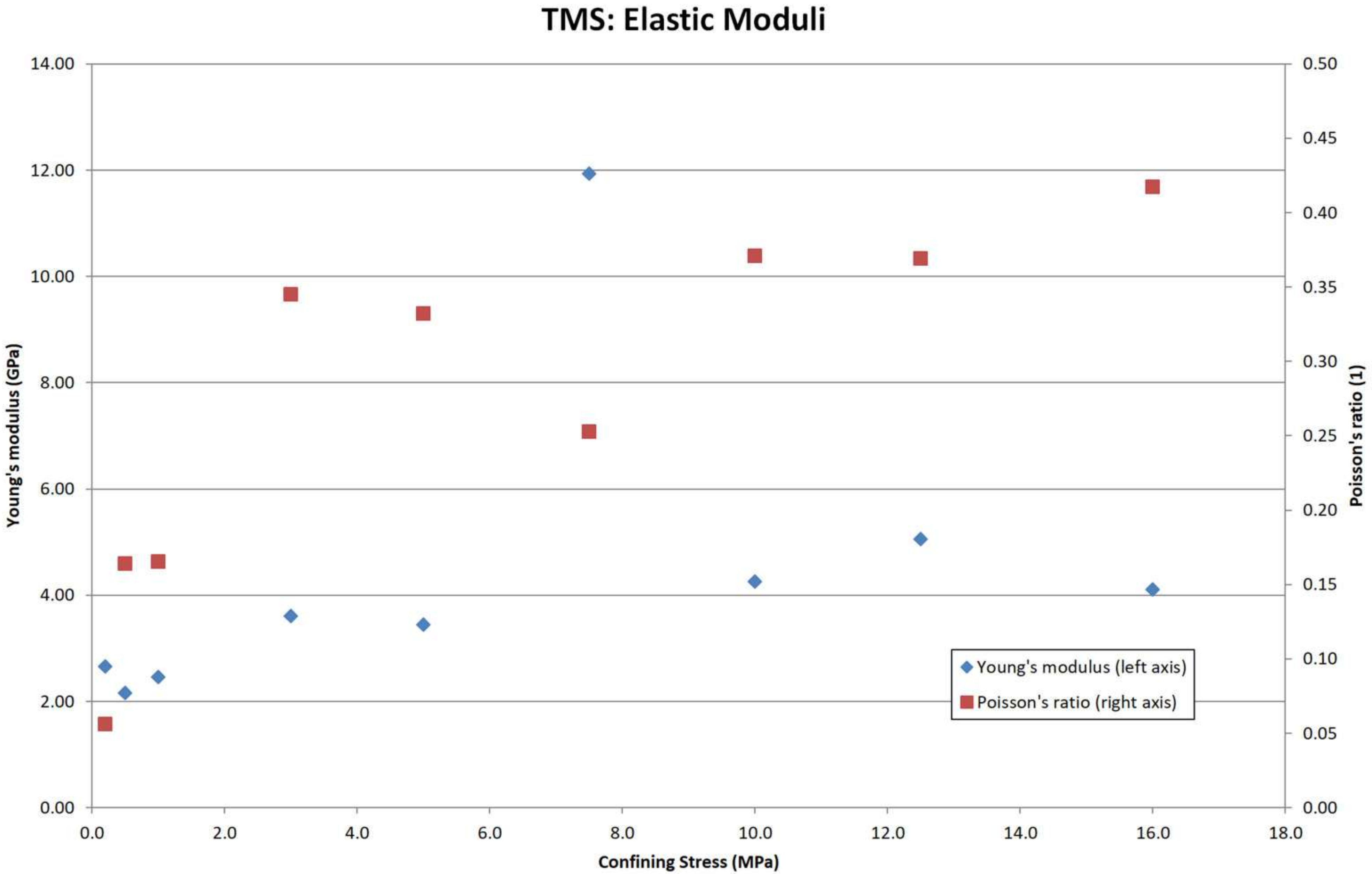
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

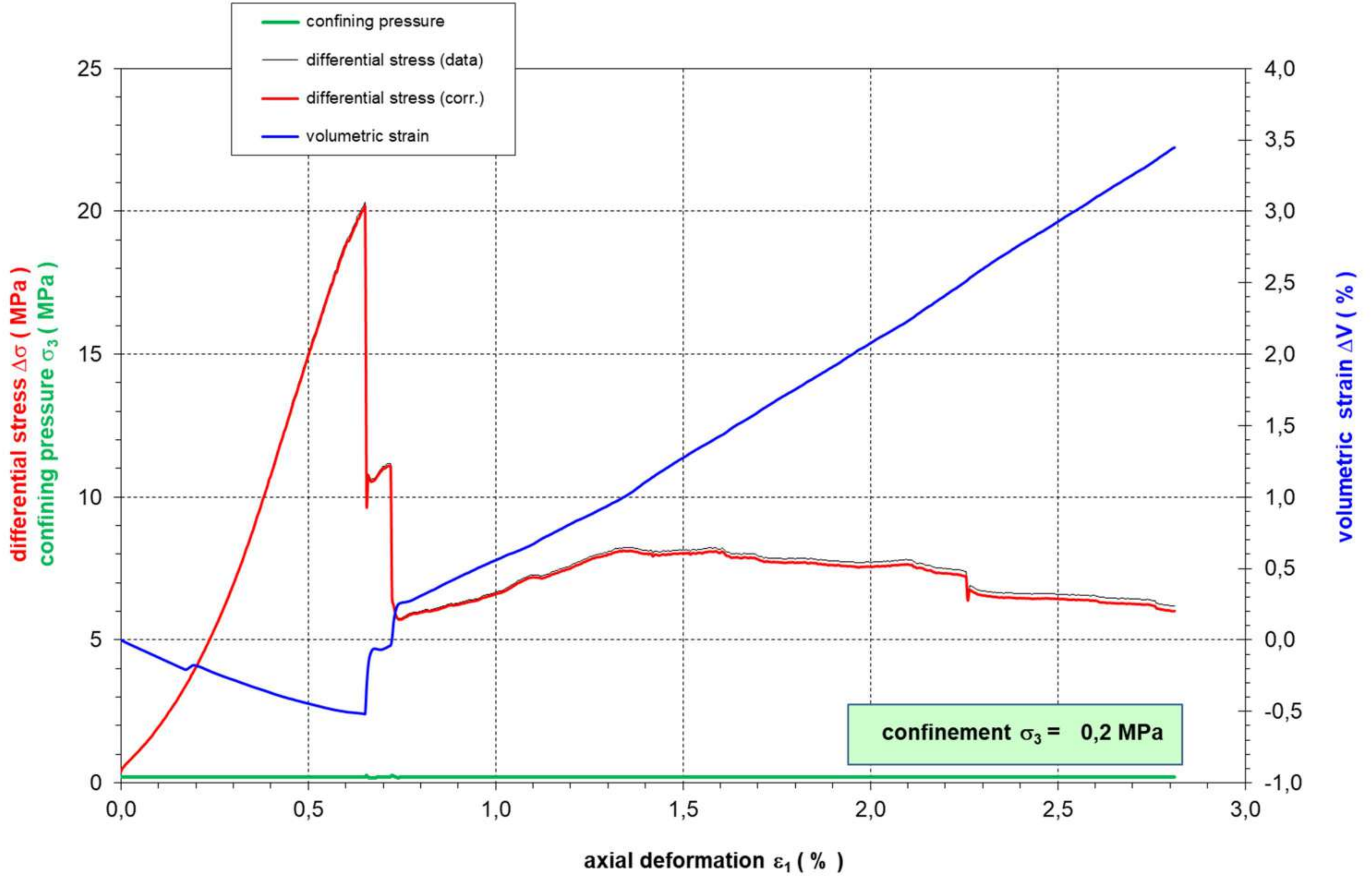


70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
differential stress (MPa)
0,0
1,0
2,0
3,0
4,0
5,0
6,0
axial deformation (%)
0.2 MPa
0.5 MPa
1,0 MPa
3,0 MPa
5,0 MPa
7,5 MPa
10,0 MPa
12,5 MPa
16,0 MPa



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH	**Triaxial strength tests (TC_nat)** **Unit – TMS (Tabuleiro)** → volumetric strain vs. axial deformation; dilatancy curves	**Appendix 135** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***


TMS: Elastic Moduli
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Young's modulus (GPa)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Poisson's ratio (1)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Confining Stress (MPa)
Young's modulus (left axis)
Poisson's ratio (right axis)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

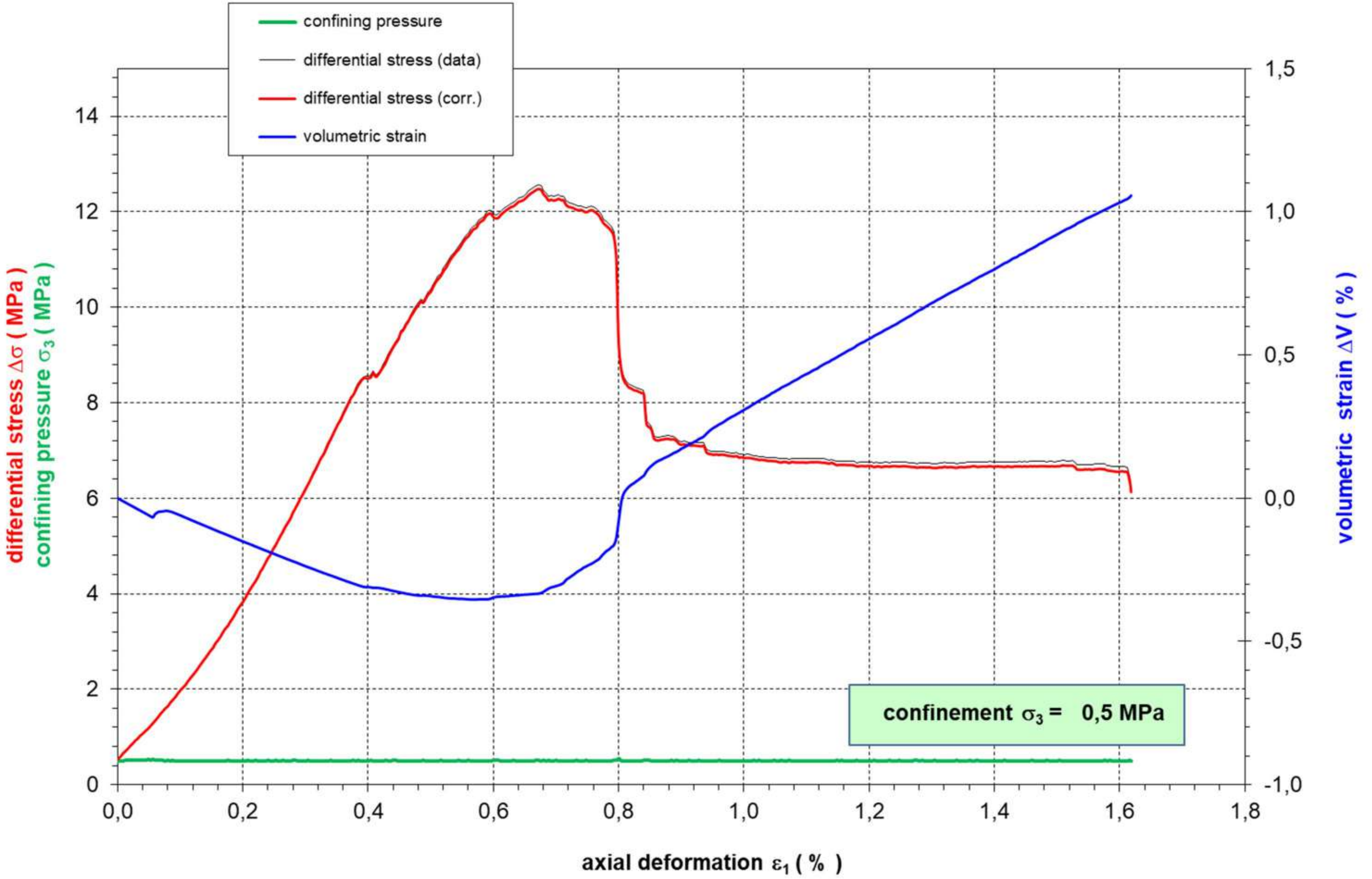
Triaxial strength test (TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS006/TC_d1

Appendix 137

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

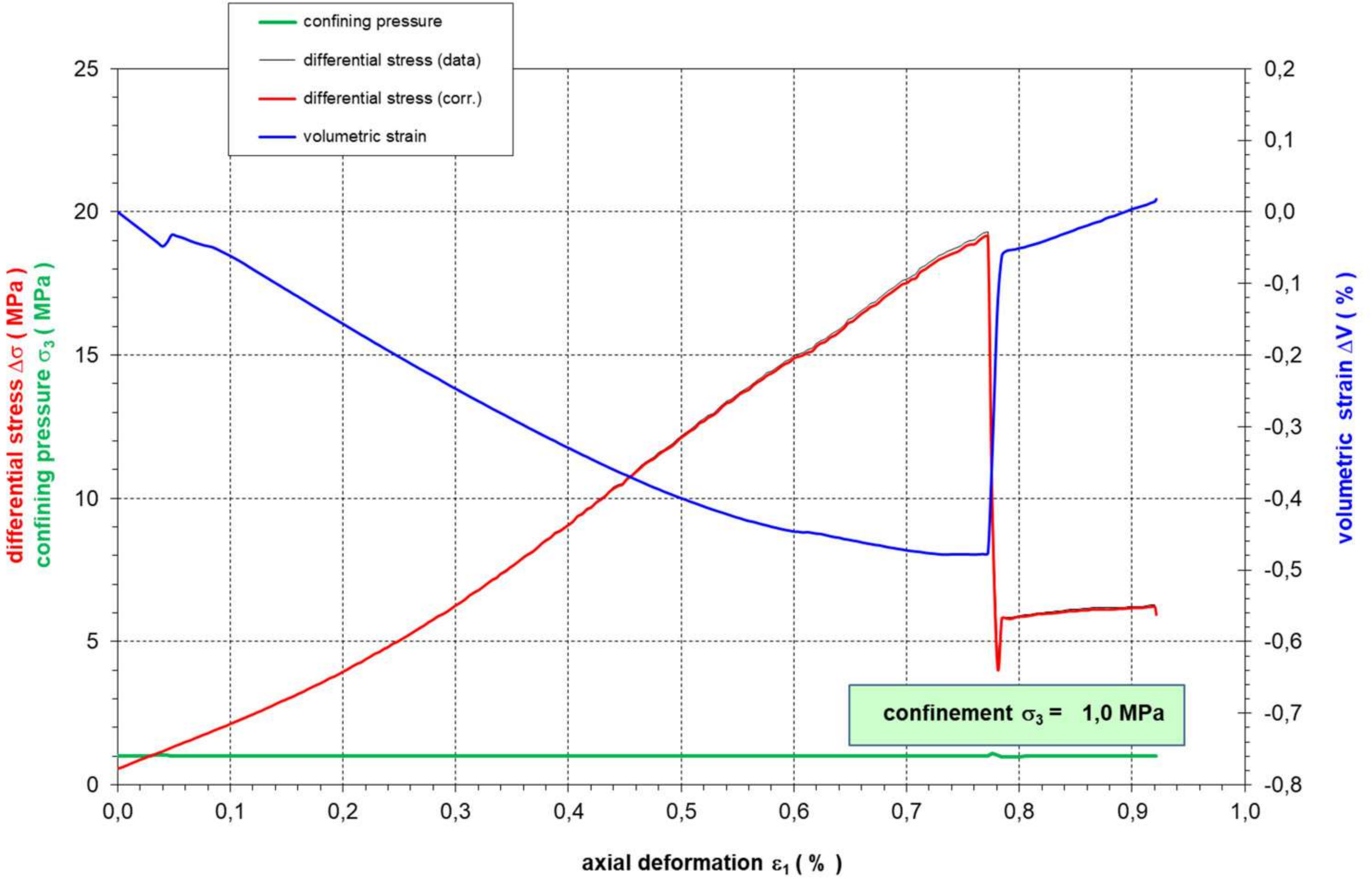
Triaxial strength test (TC_nat)

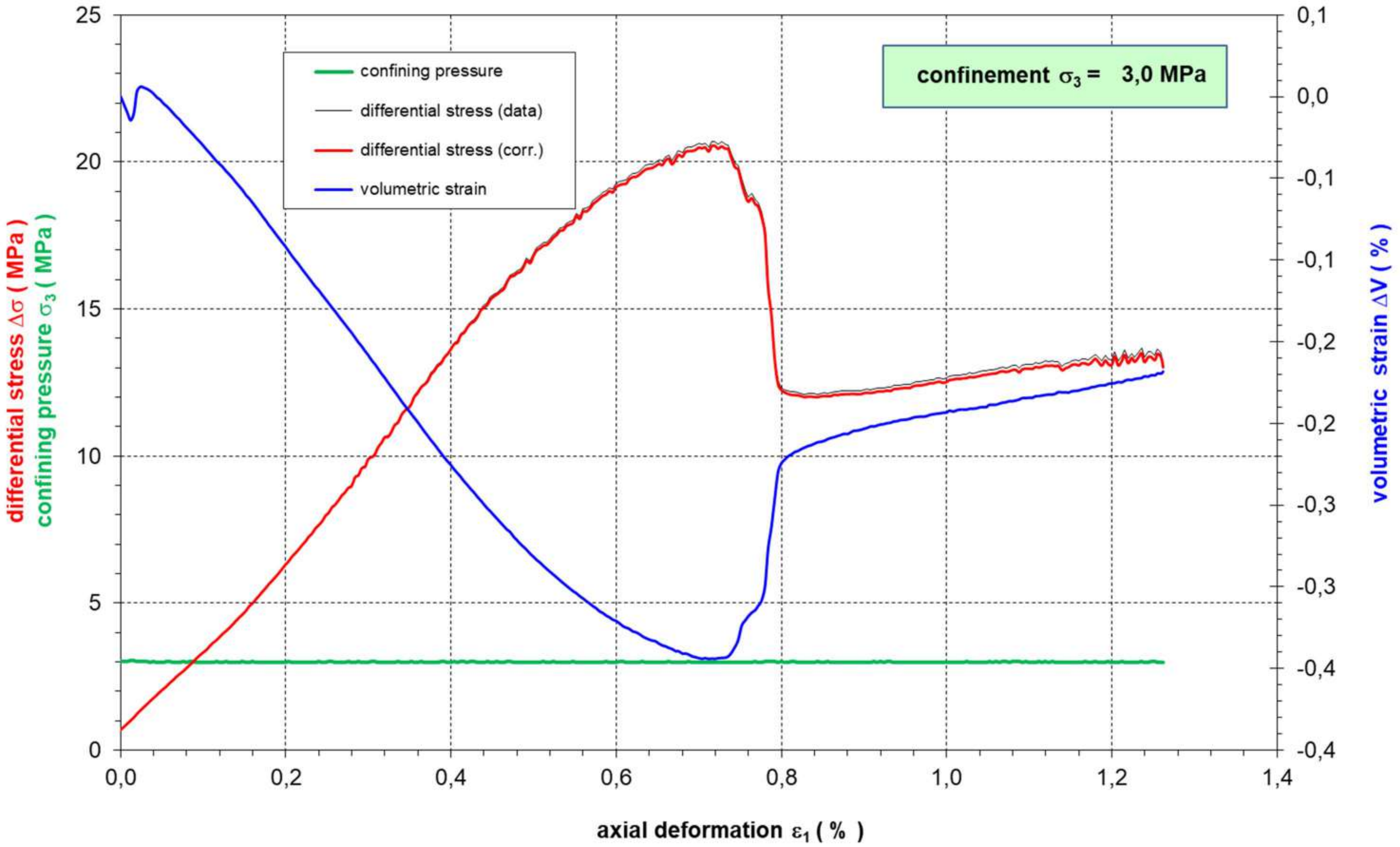
Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS027/TC_d2

Appendix 138

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"


confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
confinement σ3 = 1,0 MPa
25
20
15
10
5
0
0,2
0,1
0,0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0



INSTITUT FÜR GEBIRGSMECHANIK GMBH

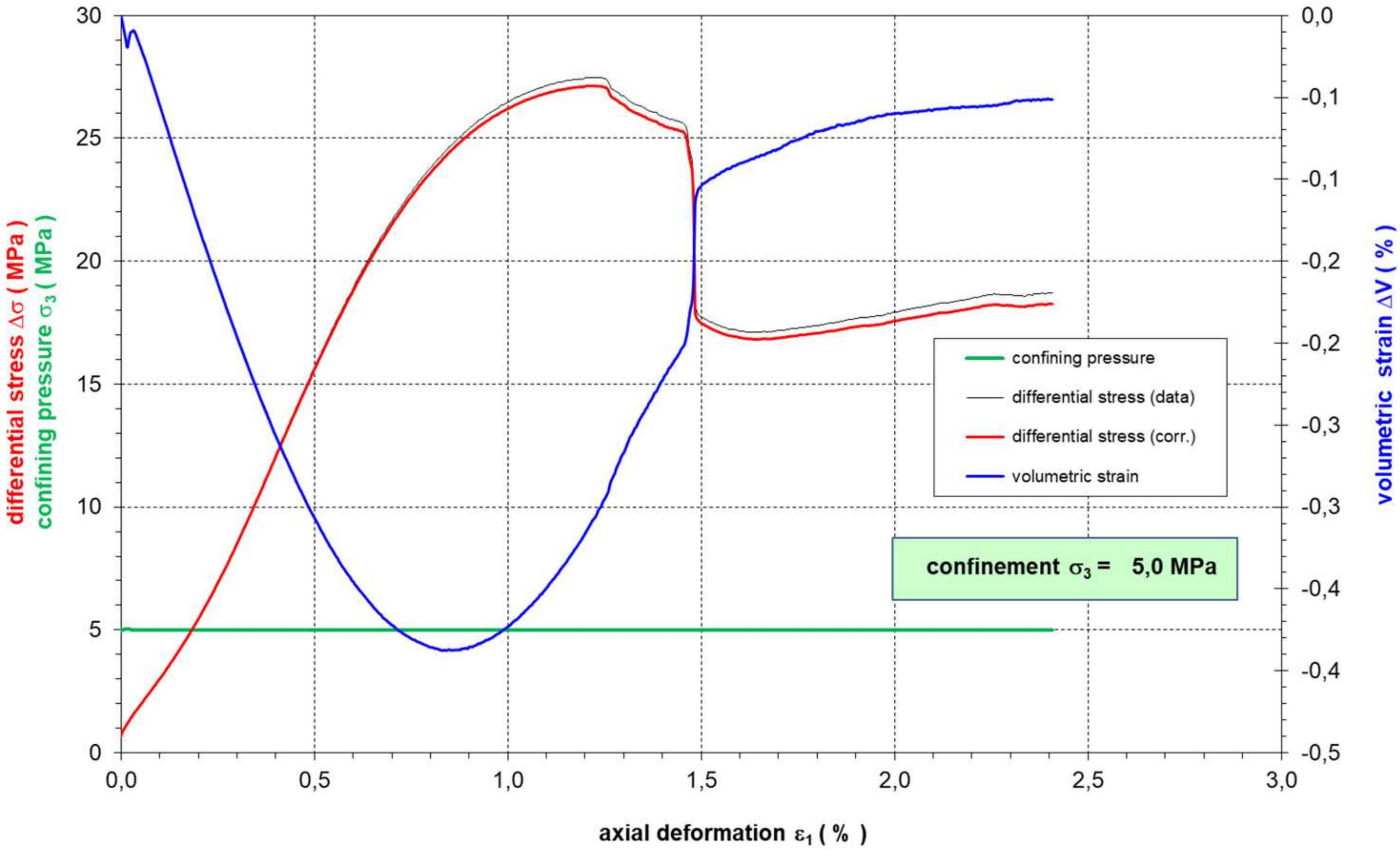
Triaxial strength test (TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS054/TC_d4

Appendix 140

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

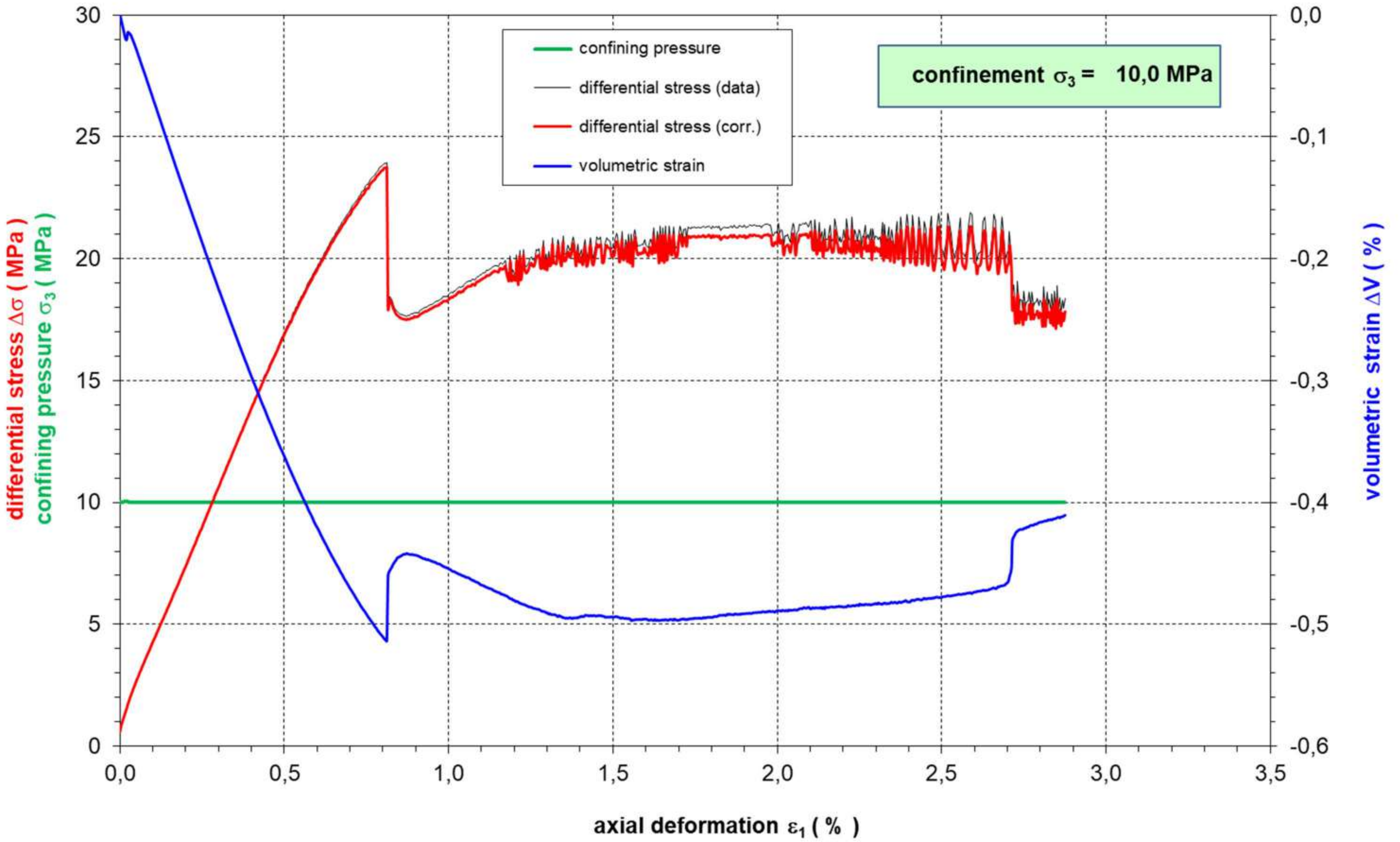
Triaxial strength test (TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS116/TC_d5

Appendix 141

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

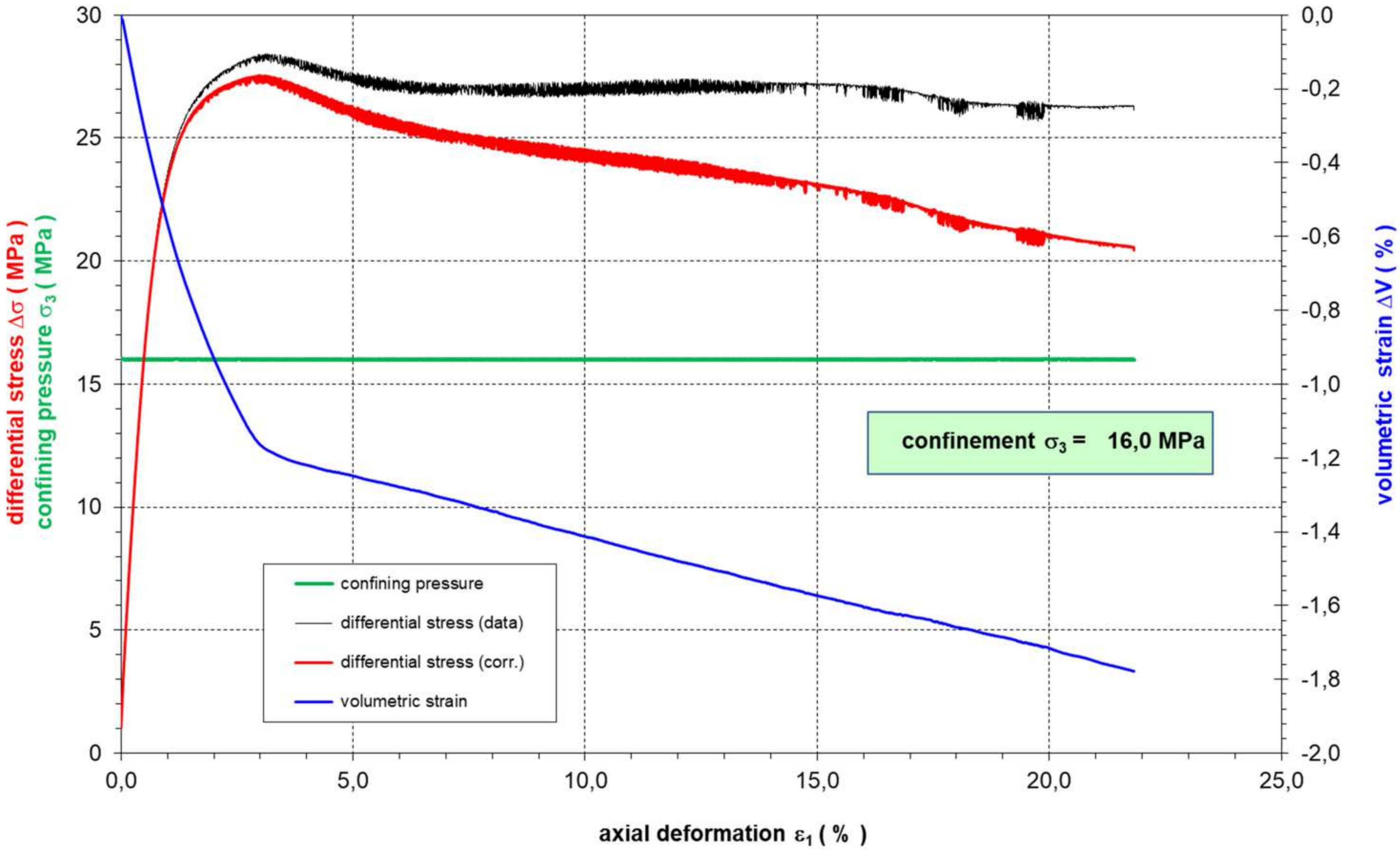
Triaxial strength test (TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TM103/TC_d6

Appendix 142

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

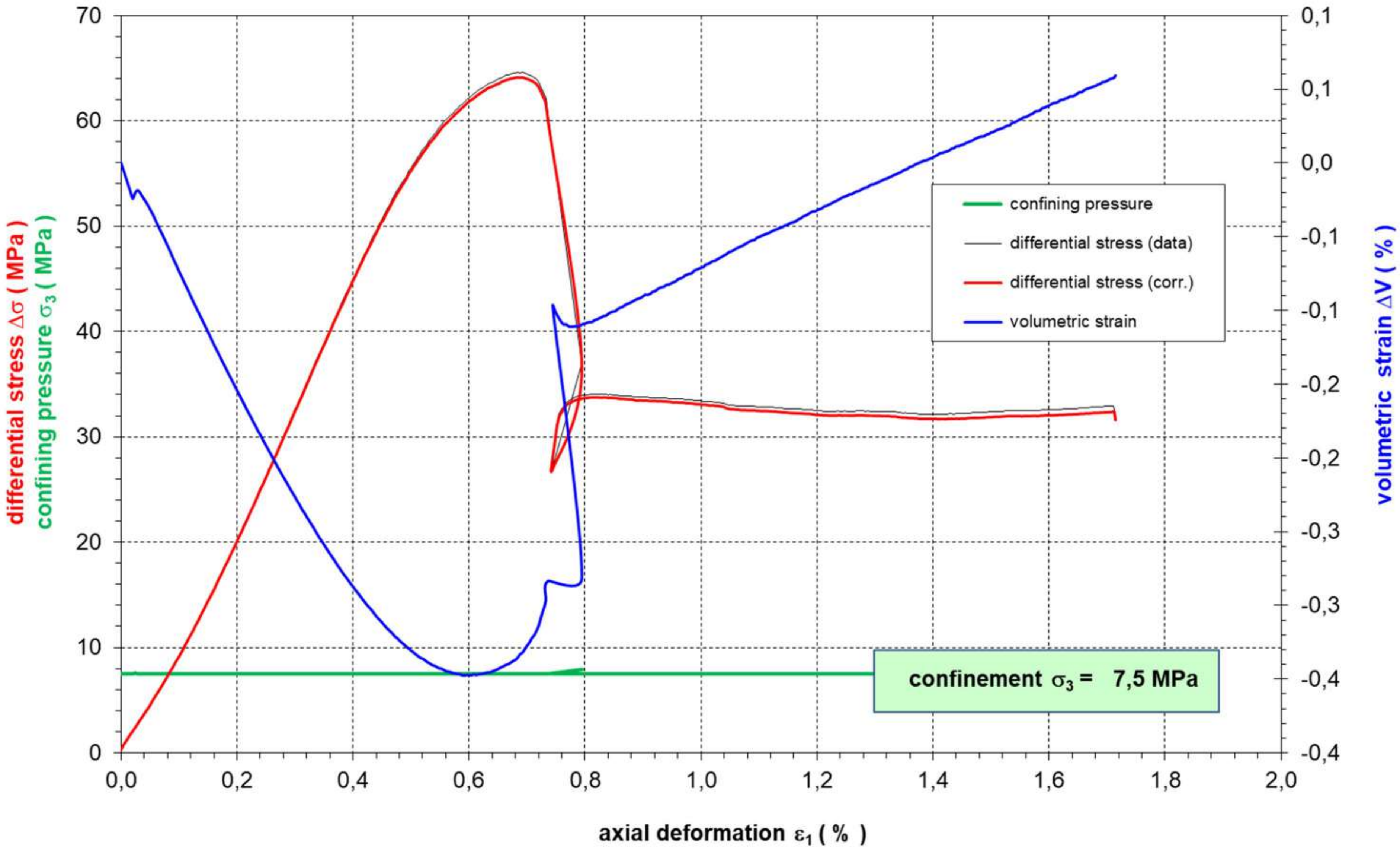
Triaxial strength test (TC_nat)

Unit – TMS (Tabuleiro)

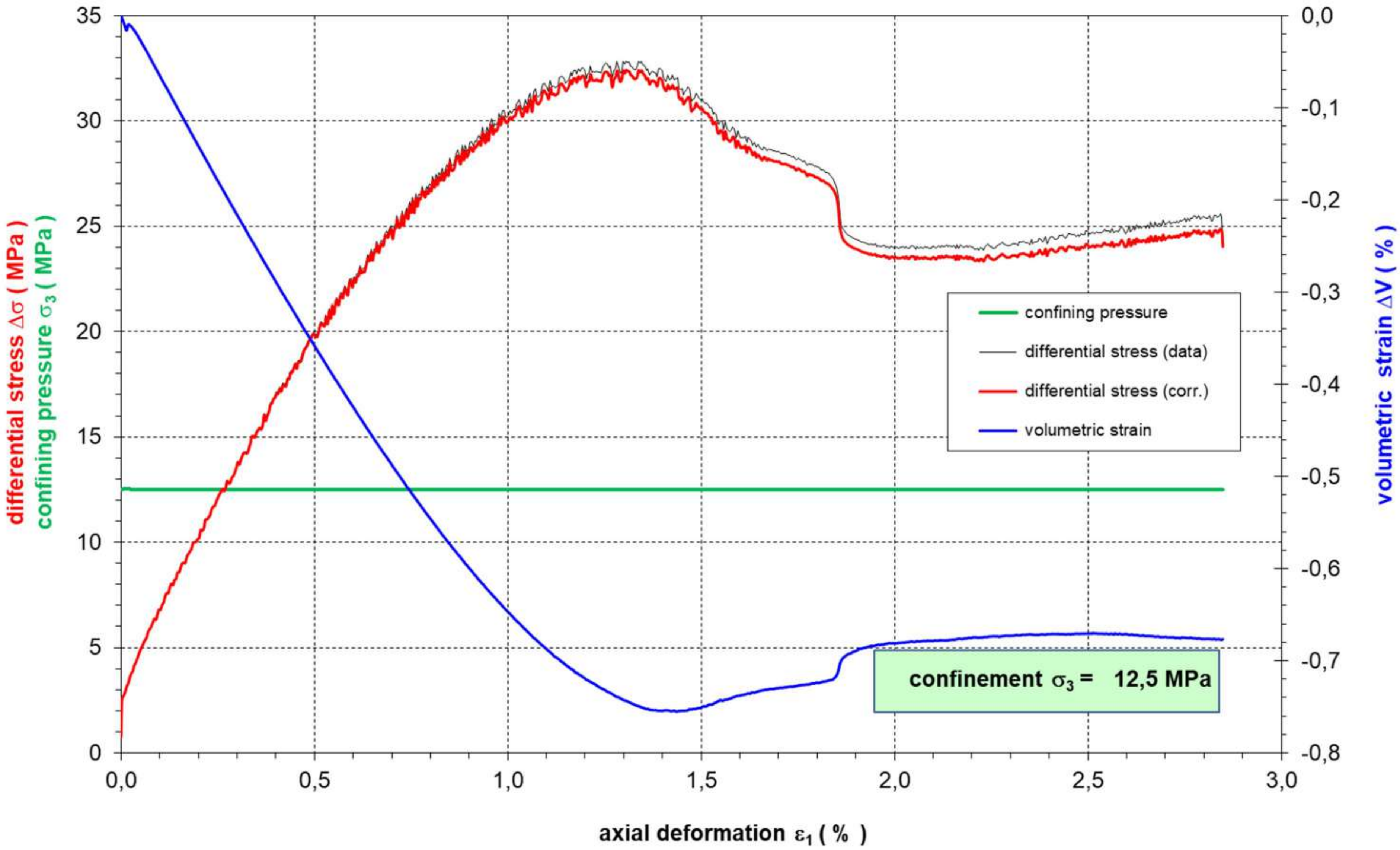
→ stress-strain behavior; sample 743/TMS112/TC_d7

Appendix 143

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial strength test (TC_nat)** **Unit – TMS (Tabuleiro)** → stress-strain behavior; sample 743/TMS114/TC_d8	**Appendix 144** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***

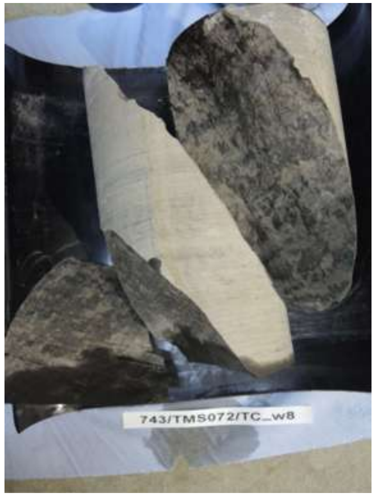


35
30
25
20
15
10
5
0
0,0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
0,0
0,5
1,0
1,5
2,0
2,5
3,0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 12,5 MPa

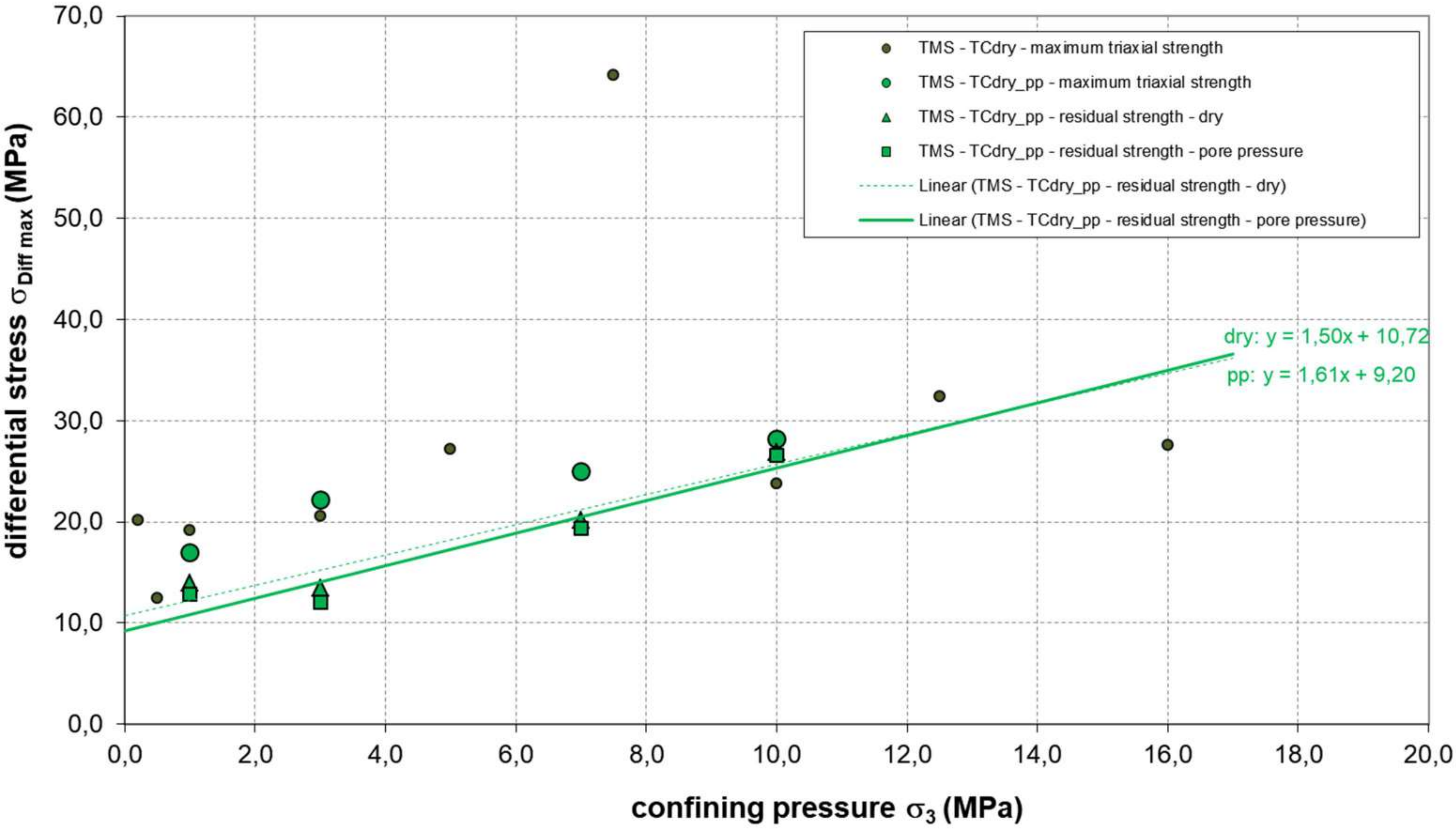
IfG - Lab-No.	743/TMS005/TC_w1_pp	743/TMS045/TC_w2_pp	743/TMS044/TC_w5_pp	743/TMS072/TC_w8_pp
Rock Type / Unit	TMS	TMS	TMS	TMS
Sample	TMS-005	TMS-045	TMS-046	TMS-072
Depth (m)				
Length l (mm) =	200.553	184.090	201.003	191.950
Diameter d (mm) =	100.60	100.09	99.488	100.41
Ratio l_o/d_o =	1.99	1.84	2.02	1.91
Mass M (g) =	4096.90	3307.2	3569.4	3465.7
Area A (cm^2) =	79.485	78.681	77.738	79.185
Volume V (cm^3) =	1594.10	1448.44	1562.55	1519.96
Density ρ (g/cm^3) =	2.570	2.283	2.284	2.280
US L (h) - p	-	-	-	-
US Q1 (a/c) - p	16.52	31.21	-	33.67
US Q2 (b/d) - p	16.64	31.61	-	33.41
US L (h) - s	-	-	-	-
US L (h) - p(s)	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	6.09	3.21	-	2.98
$V_{p\text{-radial: b-d}}$ (km/s) =	6.05	3.17	-	3.01
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-
E_d (GPa) =	-	-	-	-
K_d (GPa) =	-	-	-	-
G_d (GPa) =	-	-	-	-
ν_d =	-	-	-	-
	TC_PorePressure	TC_PorePressure	TC_PorePressure	TC_PorePressure
Temp. (°C)	**23**	**23**	**23**	**23**
σ_3 (MPa) =	1.0	3.0	10.0	7.0
Pore pressure (MPa) =	0.5	1.5	5.0	3.5
σ_{Dil} (MPa) =	-	-	-	-
ΔV_{Dil} (%) =	-	-	-	-
ε_{Dil} (%) =	-	-	-	-
σ_{Fail} (MPa) =	16.94	22.16	28.20	24.92
ΔV_{Fail} (%) =	-	-	-	-
ε_{Fail} (%) =	1.33	1.15	1.36	1.03
σ_{1Fail} (MPa) =	17.94	25.16	38.20	31.92
$\sigma_{res.nat}$ (MPa) =	13.98	13.40	26.82	20.17
$\sigma_{res.pore}$ (MPa) =	12.79	11.99	26.55	19.37

BEFORE:

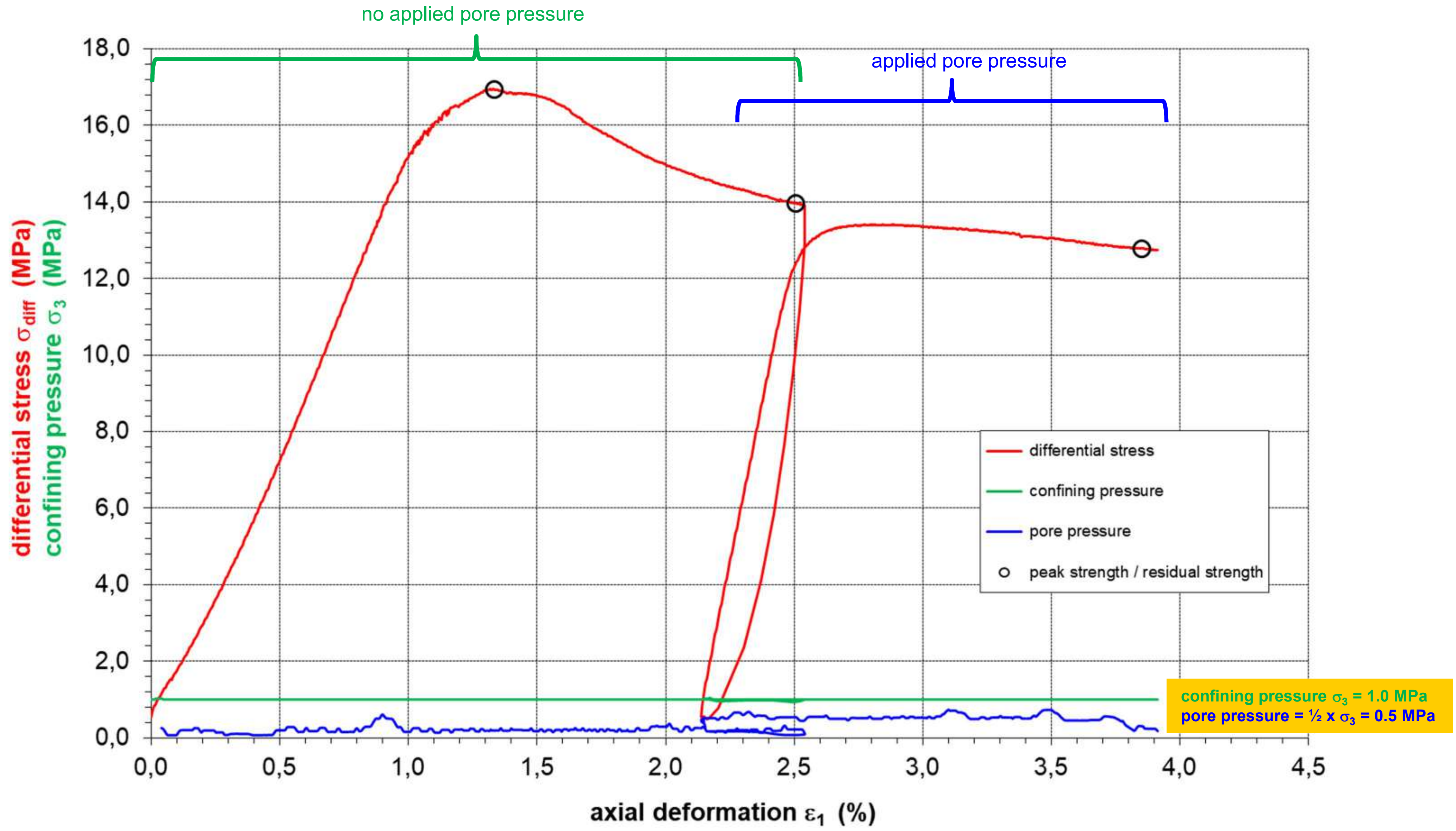
AFTER:



σ_3 = 1.0 MPa σ_{pp} = 0.5 MPa	σ_3 = 3.0 MPa σ_{pp} = 1.5 MPa	σ_3 = 10.0 MPa σ_{pp} = 5.0 MPa	σ_3 = 7.0 MPa σ_{pp} = 3.5 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Samples for triaxial tests (with pore pressure application after TC_nat)** **Unit – TMS (Tabuleiro)** → maximum strength values dependent on the radial stress	**Appendix 148** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

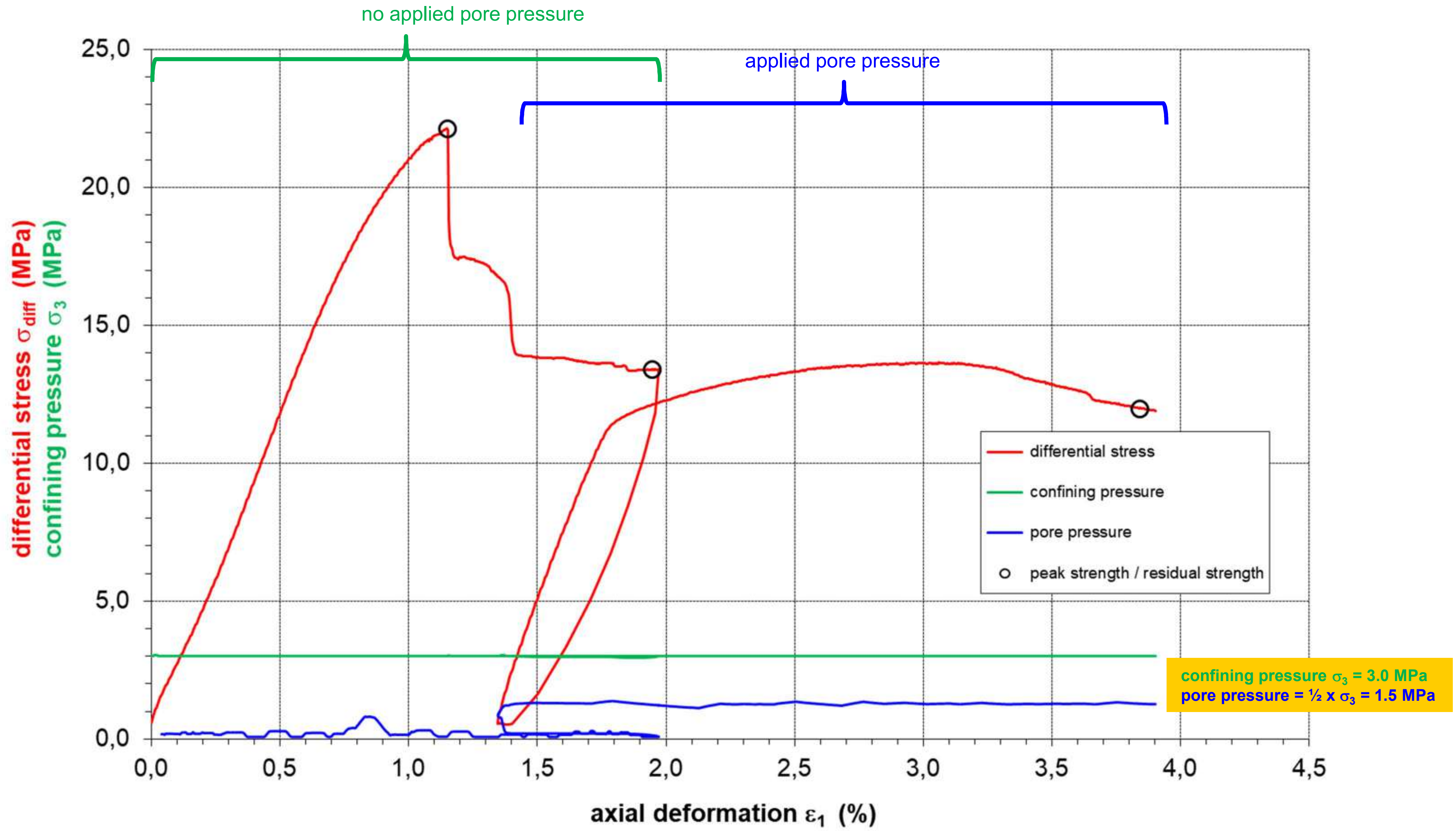
triaxial strength test (with pore pressure application after TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS005/TC_w1_pp

Appendix 149

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

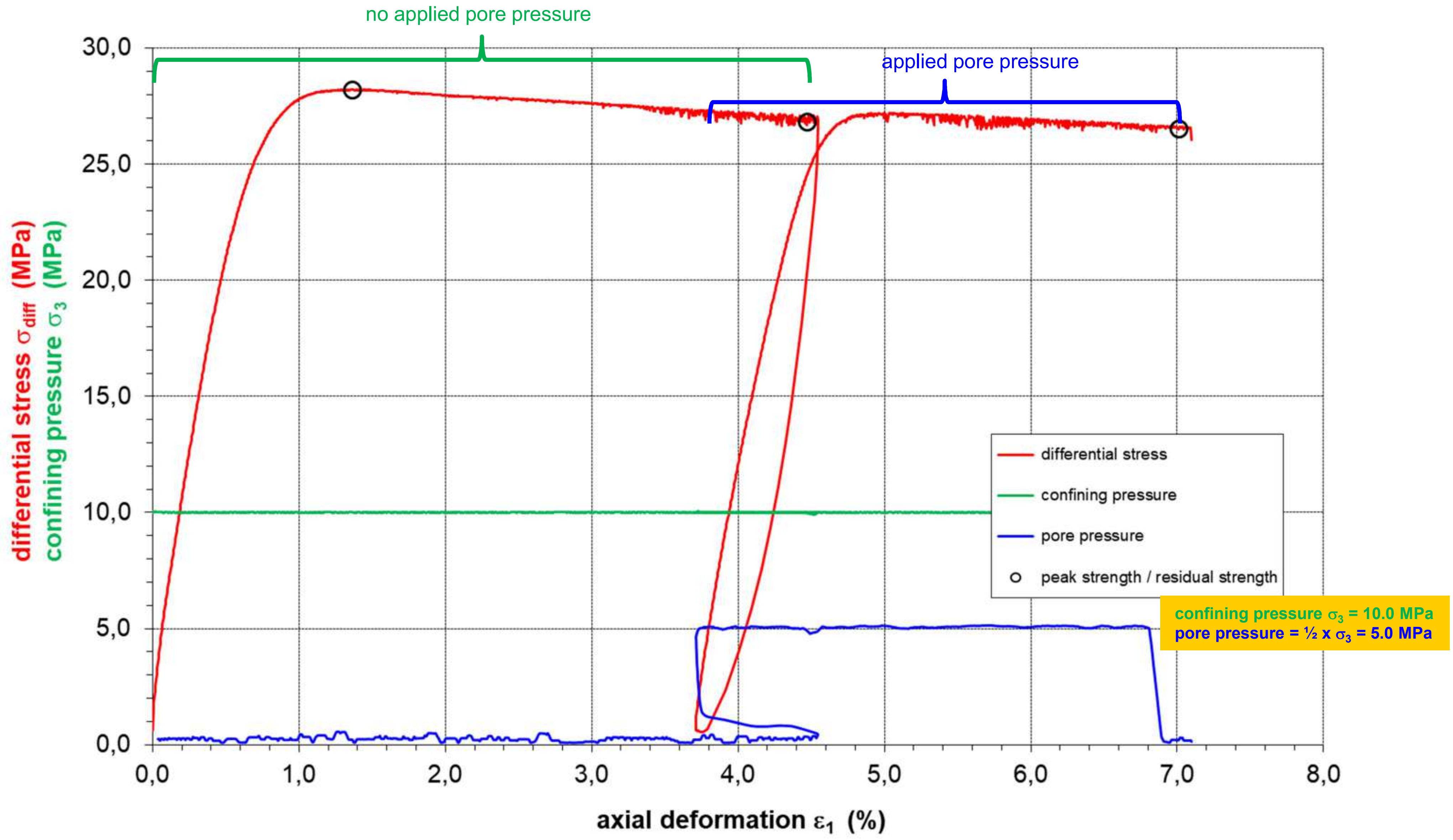
triaxial strength test (with pore pressure application after TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS045/TC_w2_pp

Appendix 150

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

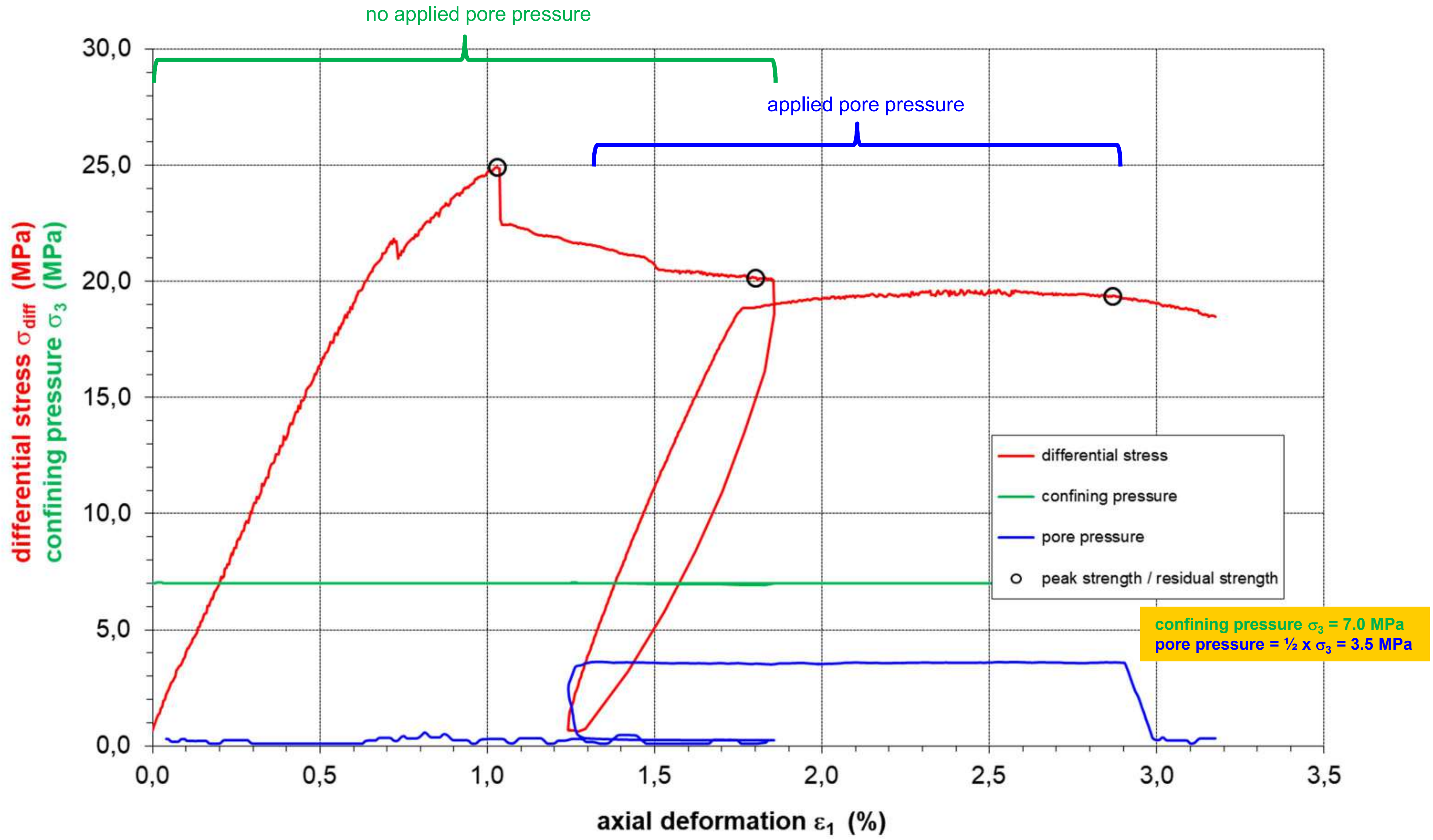
triaxial strength test (with pore pressure application after TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS044/TC_w5_pp

Appendix 151

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

triaxial strength test (with pore pressure application after TC_nat)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS072/TC_w8_pp

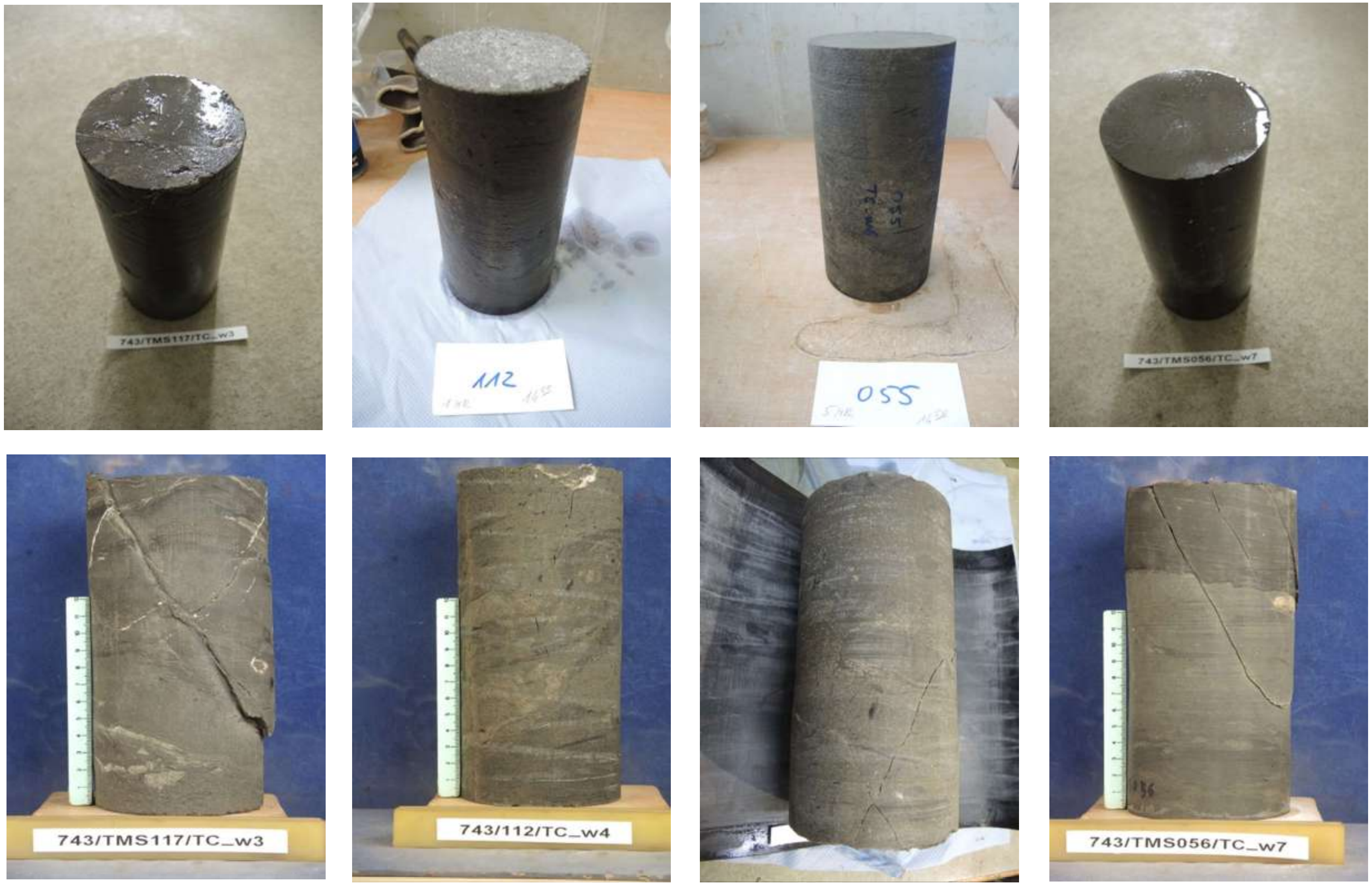
Appendix 152

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

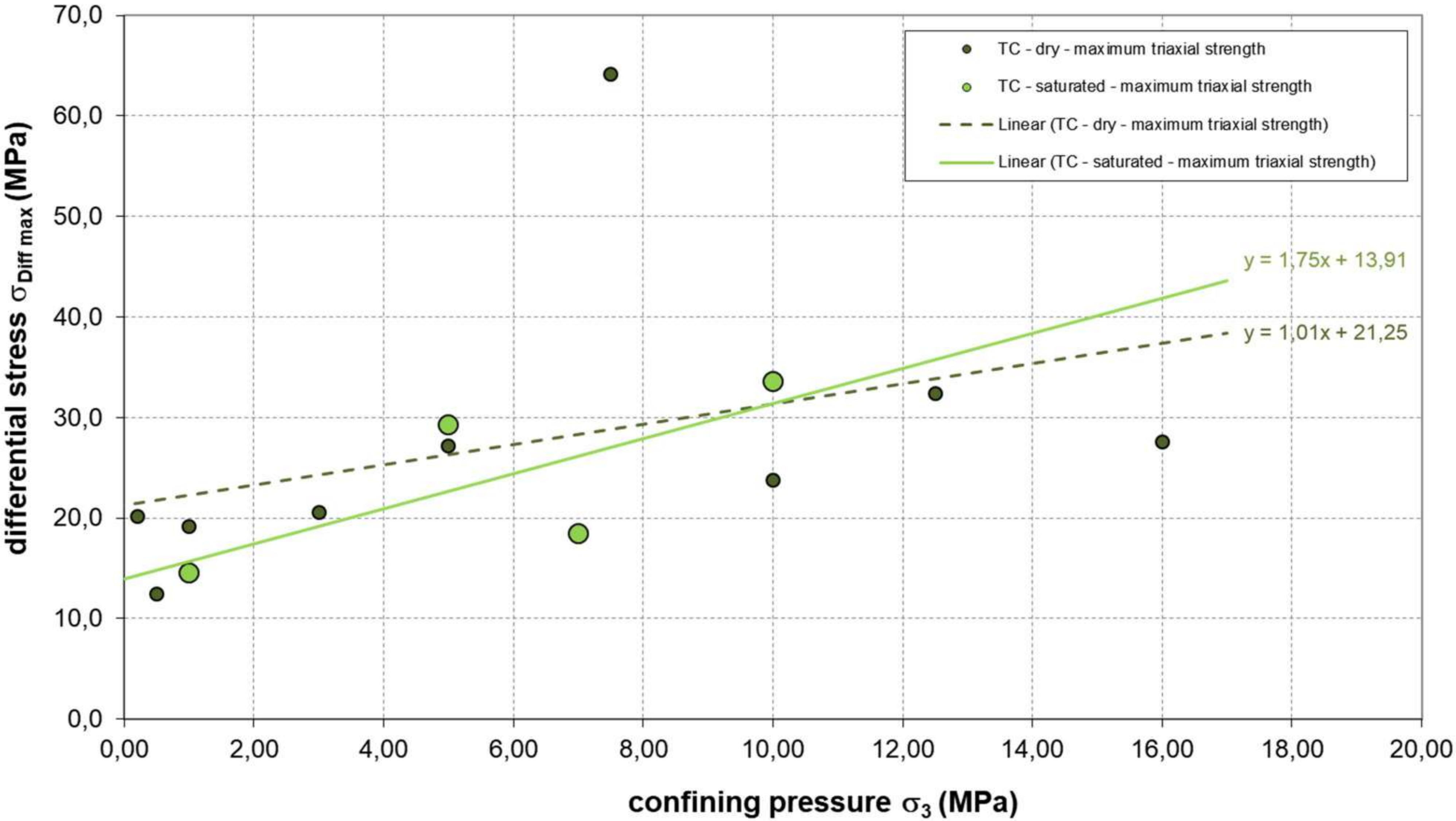
IfG - Lab-No.	743/TMS117/TC_w3_sat		743/TMS112/TC_w4_sat		743/TMS055/TC_w6_sat		743/TMS056/TC_w7_sat	
Rock Type / Unit	TMS		TMS		TMS		TMS	
Sample	TMS-117		TMS-112		TMS-055		TMS-056	
Depth (m)								
	natural	saturated	natural	saturated	natural	saturated	natural	saturated
Length l (mm) =	200.010	200.253	198.818	198.508	200.360	200.630	200.118	200.513
Diameter d (mm) =	99.247	99.052	98.997	99.047	100.115	100.253	99.838	99.873
Ratio l_o/d_o =	2.02	2.02	2.01	2.00	2.00	2.00	2.00	2.01
Mass M (g) =	3727.20	3448.10	3248.30	3275.10	3835.70	3865.00	3525.20	3566.70
Area A (cm^2) =	77.361	77.058	76.972	77.050	78.721	78.938	78.286	78.340
Volume V (cm^3) =	1547.31	1543.10	1530.34	1529.50	1577.25	1583.73	1566.63	1570.83
Density ρ (g/cm^3) =	2.409	2.235	2.123	2.141	2.432	2.440	2.250	2.271
US L (h) - p	-	-	-	-	-	-	-	-
US Q1 (a/c) - p	35.18	-	-	-	26.40	-	29.83	-
US Q2 (b/d) - p	35.18	-	-	-	27.07	-	29.01	-
US L (h) - s	-	-	-	-	-	-	-	-
US L (h) - p(s)	-	-	-	-	-	-	-	-
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-	-	-	-
$V_{p\text{-radial: a-c}}$ (km/s) =	2.82	-	-	-	3.79	-	3.35	-
$V_{p\text{-radial: b-d}}$ (km/s) =	2.82	-	-	-	3.70	-	3.44	-
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-	-	-	-
E_d (GPa) =	-	-	-	-	-	-	-	-
K_d (GPa) =	-	-	-	-	-	-	-	-
G_d (GPa) =	-	-	-	-	-	-	-	-
ν_d =	-	-	-	-	-	-	-	-
	TC		TC		TC		TC	
Temp. (°C)	23	23	23	23	23	23	23	23
σ_3 (MPa) =	-	7.0	-	1.0	-	5.0	-	10.0
σ_{Dil} (MPa) =	-	17.9	-	12.8	-	29.0	-	33.2
ΔV_{Dil} (%) =	-	-0.41	-	-0.49	-	-0.41	-	-0.69
ε_{Dil} (%) =	-	3.77	-	0.84	-	0.91	-	2.18
σ_{Fail} (MPa) =	-	18.4	-	14.5	-	29.3	-	33.6
ΔV_{Fail} (%) =	-	-0.40	-	-0.43	-	-0.41	-	-0.69
ε_{Fail} (%) =	-	4.48	-	1.02	-	0.99	-	1.94
σ_{1Fail} (MPa) =	-	25.41	-	15.55	-	34.29	-	43.58

BEFORE:

AFTER:



σ_3 = 7.0 MPa | σ_3 = 1.0 MPa | σ_3 = 5.0 MPa | σ_3 = 10.0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

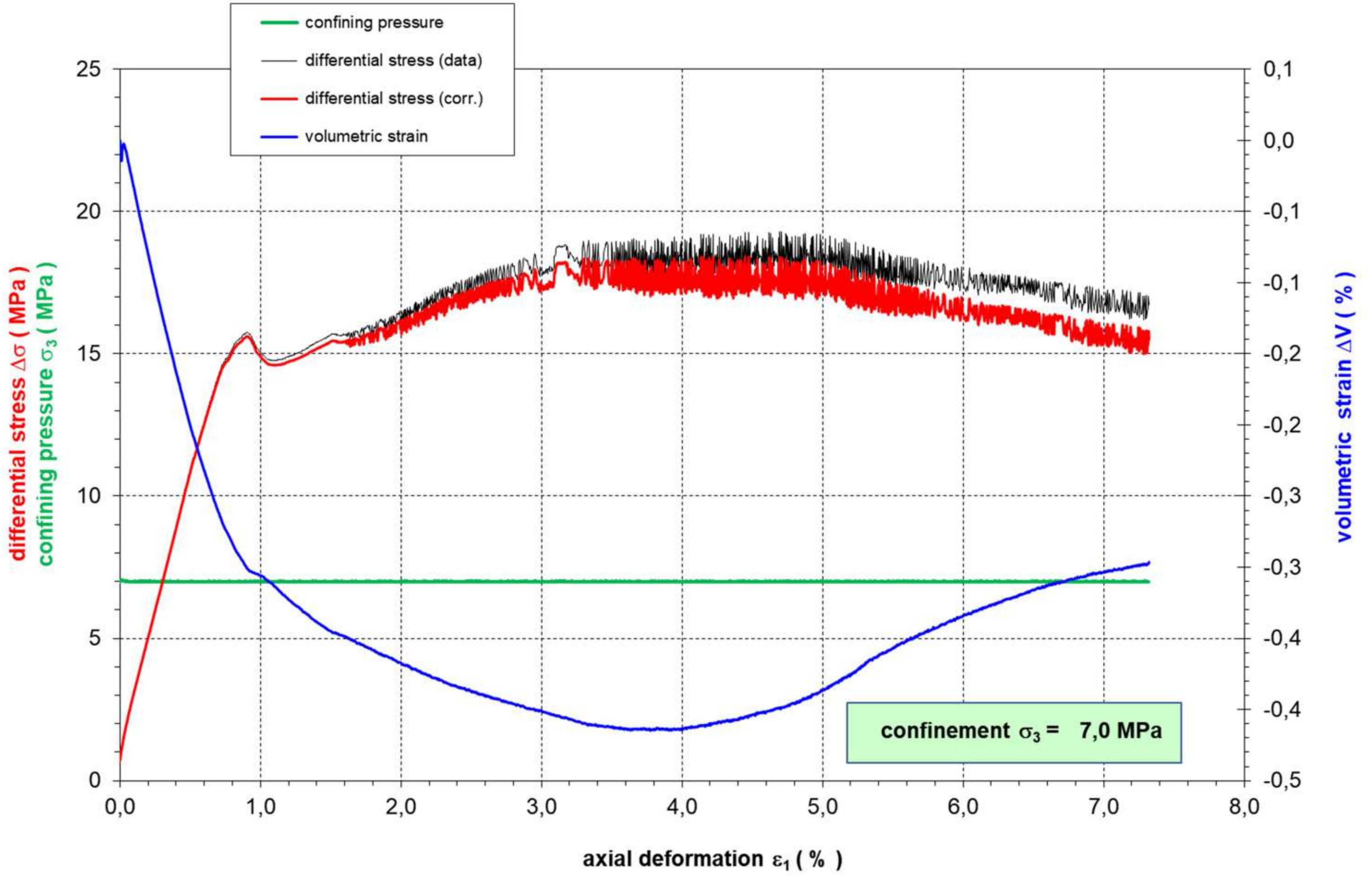
24h-saturated samples for triaxial strength tests (TC_sat)

Unit – TMS (Tabuleiro)

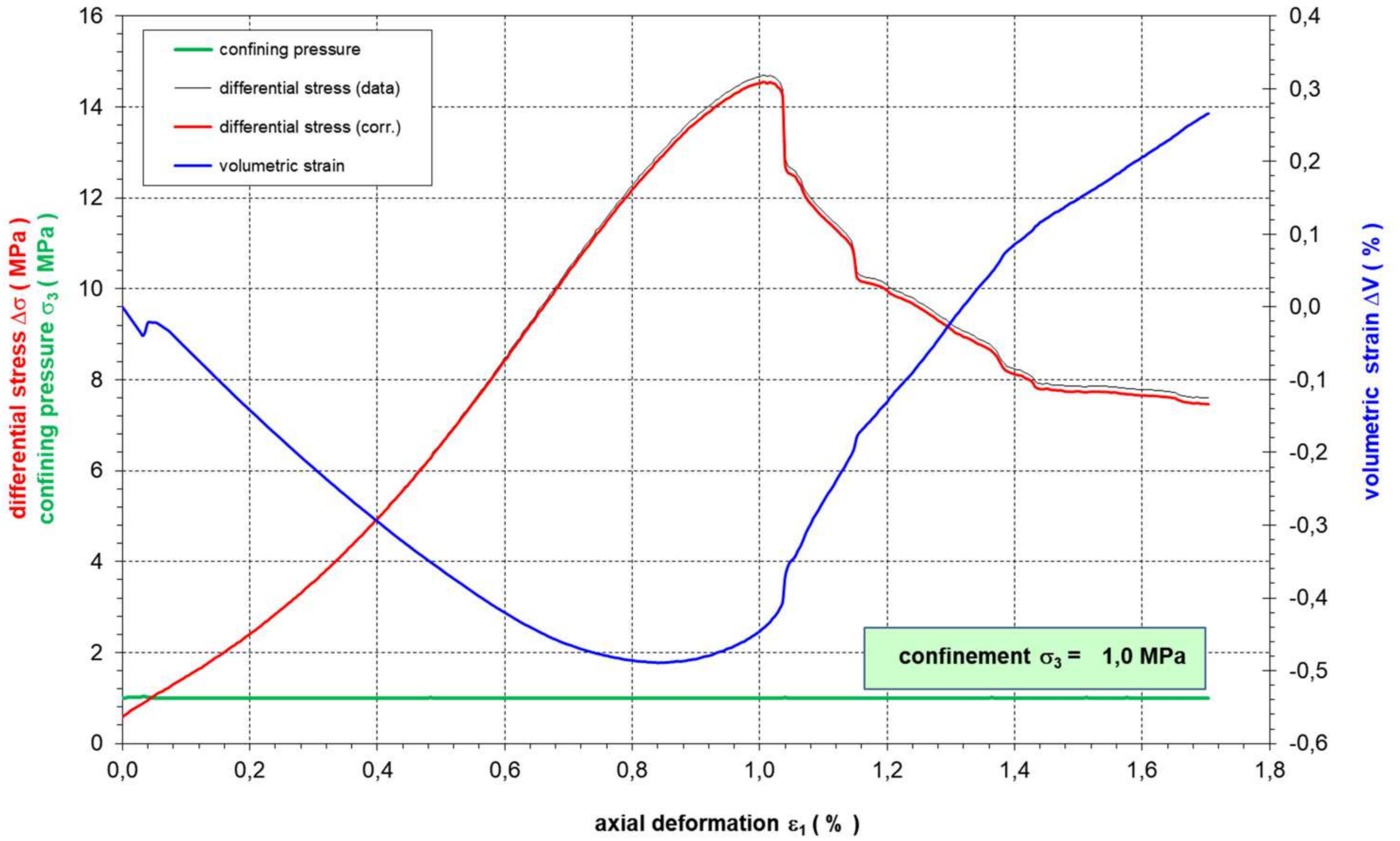
→ maximum strength values dependent on the radial stress

Appendix 155

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
differential stress Δσ (MPa)
confining pressure σ_3 (MPa)
volumetric strain ΔV (%)
axial deformation ε_1 (%)
confinement σ_3 = 7,0 MPa
25
20
15
10
5
0
0,1
0,0
-0,1
-0,2
-0,3
-0,4
-0,5
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0



INSTITUT FÜR GEBIRGSMECHANIK GMBH

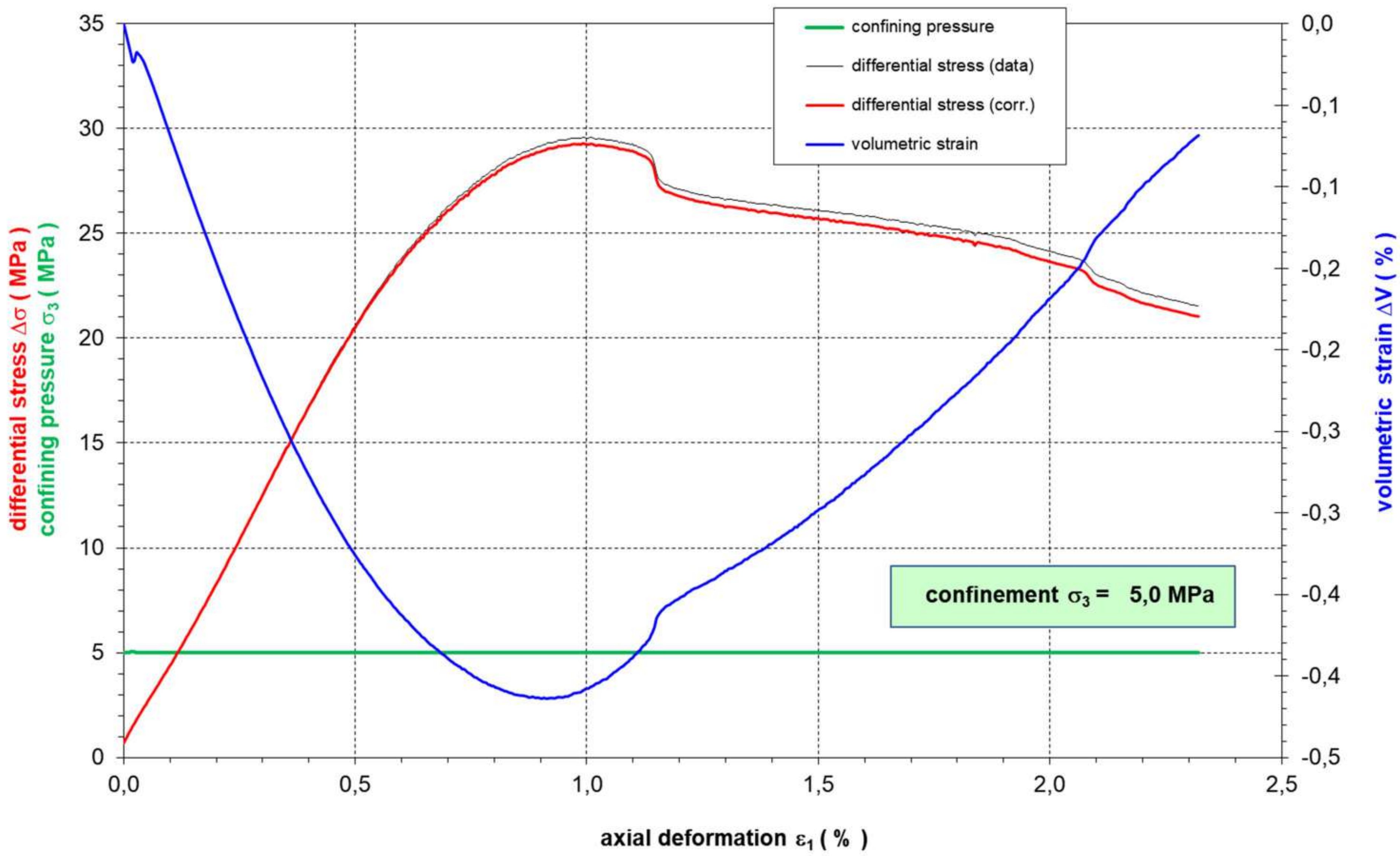
triaxial strength test (TC_sat; after 24h saturation)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS112/TC_w4_sat

Appendix 157

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

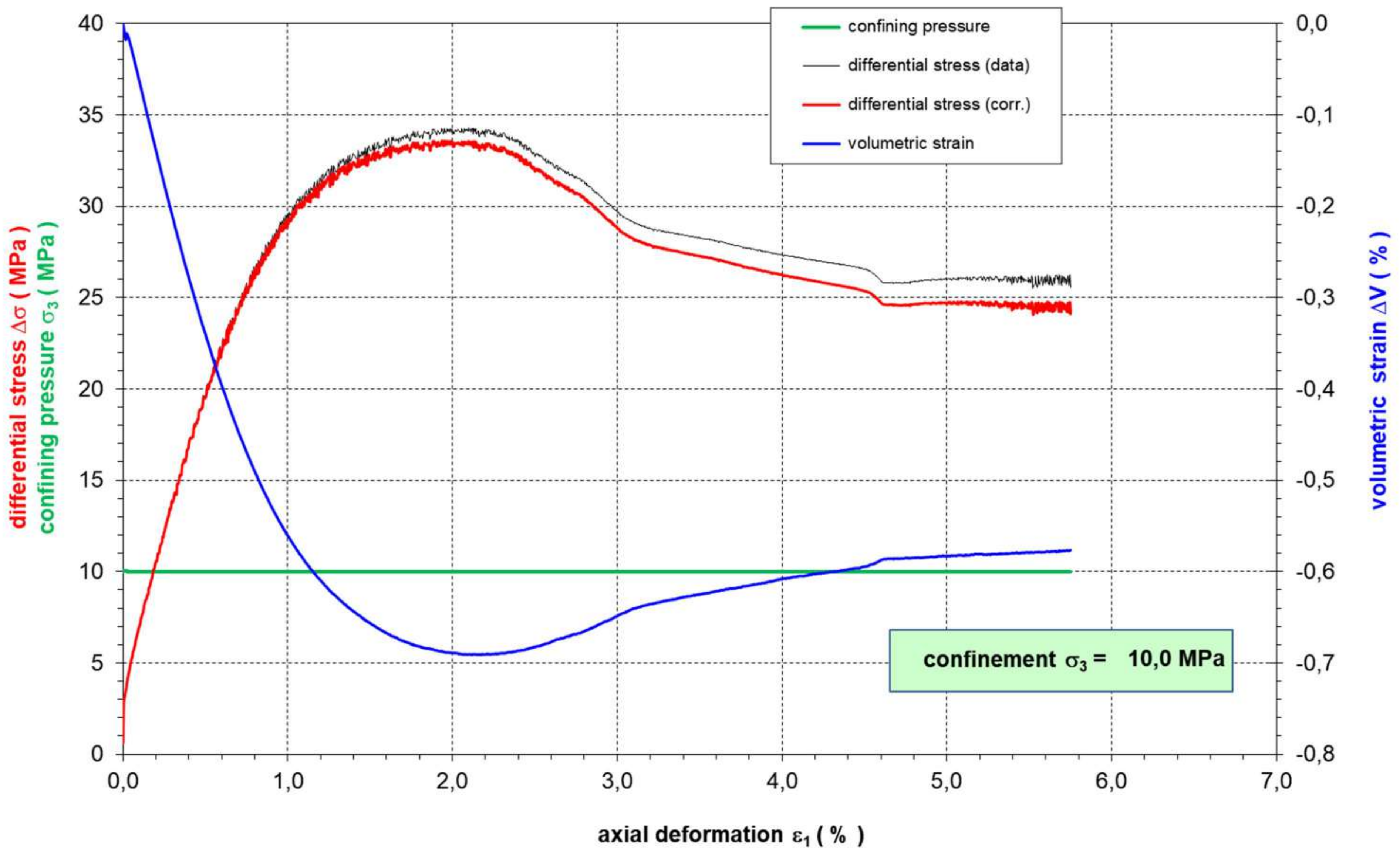
triaxial strength test (TC_sat; after 24h saturation)

Unit – TMS (Tabuleiro)

→ stress-strain behavior; sample 743/TMS055/TC_w6_sat

Appendix 158

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

triaxial strength test (TC_sat; after 24h saturation)

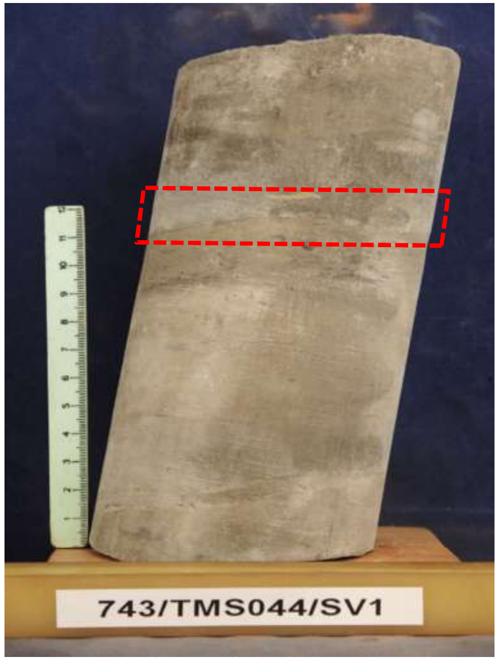
Unit – TMS (Tabuleiro)

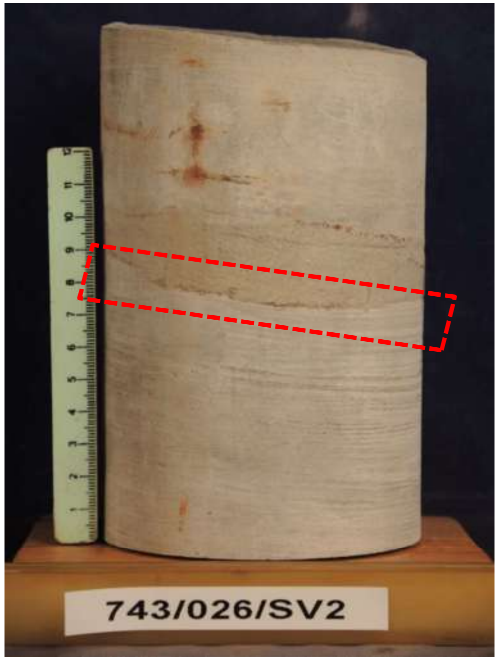
→ stress-strain behavior; sample 743/TMS056/TC_w7_sat

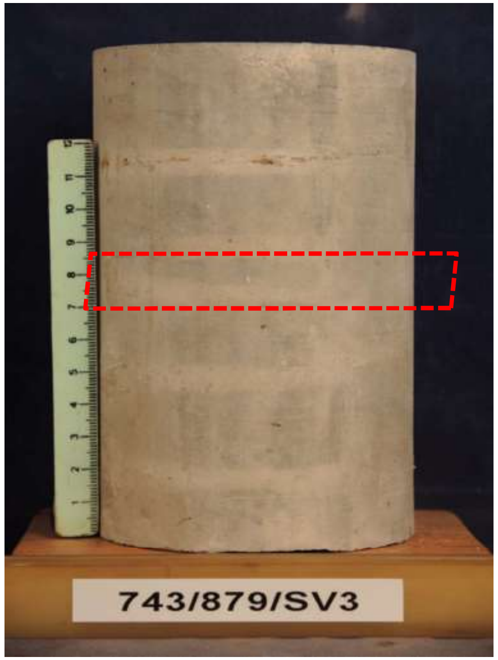
Appendix 159

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:







AFTER:

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for direct shear tests (DST)

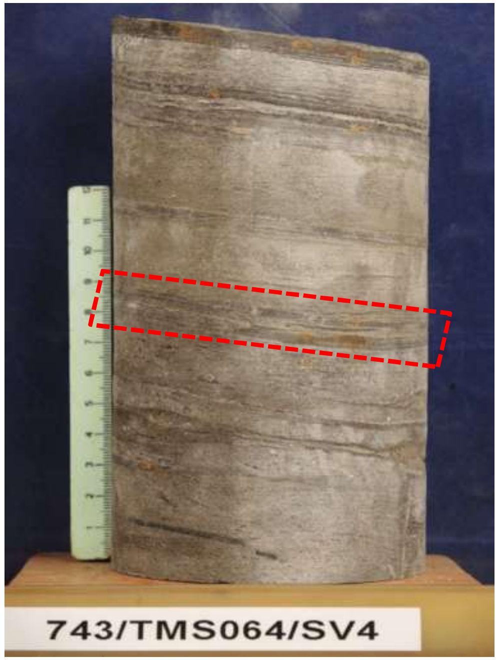
Unit – TMS (Tabuleiro)

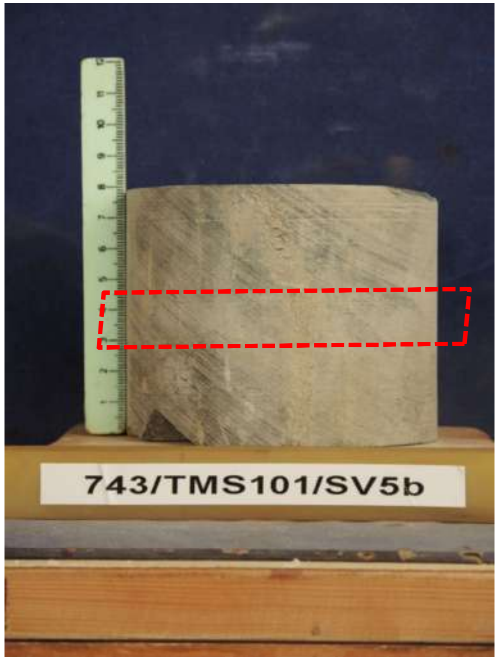
→ photo-documentation before and after the test

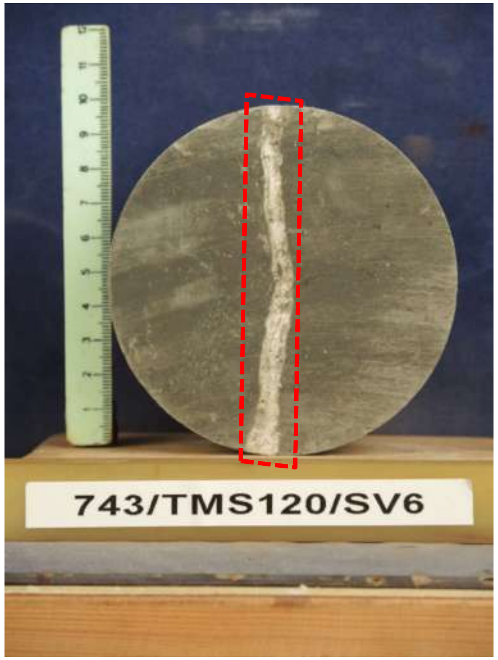
Appendix 160

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

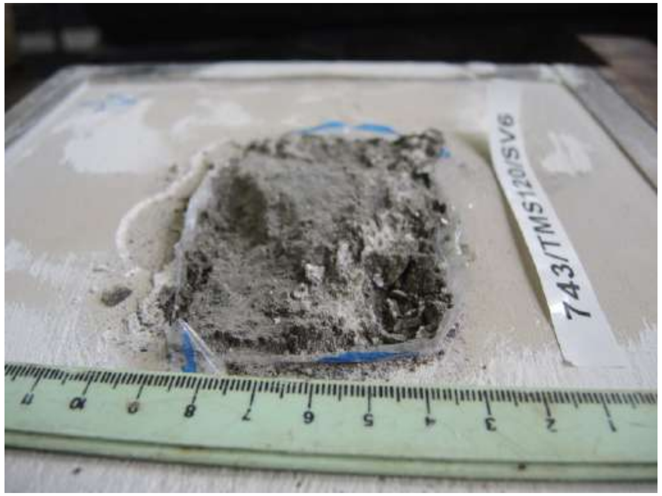
BEFORE:







AFTER:



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

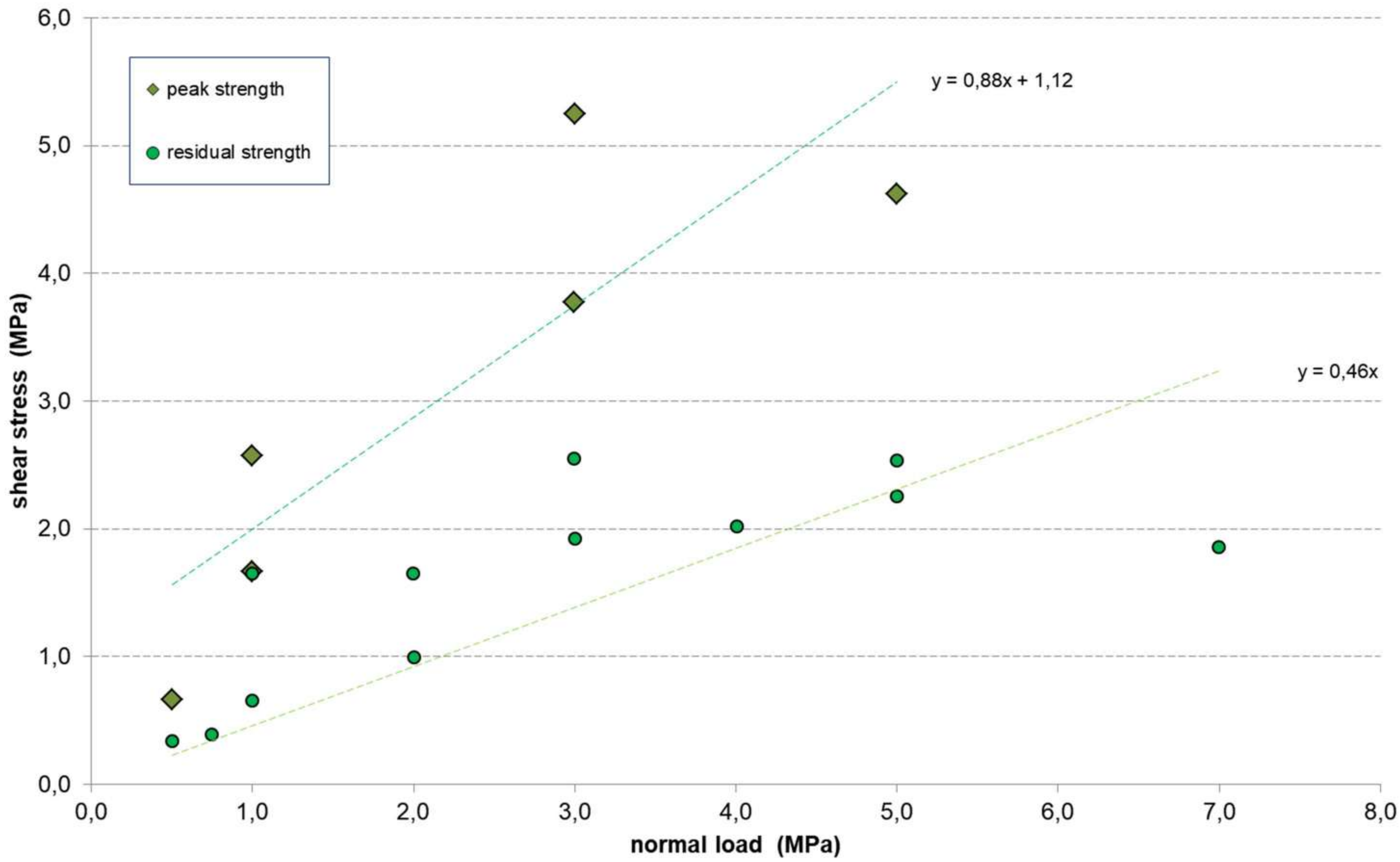
Samples for direct shear tests (DST)

Unit – TMS (Tabuleiro)

→ photo-documentation before and after the test

Appendix 161

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

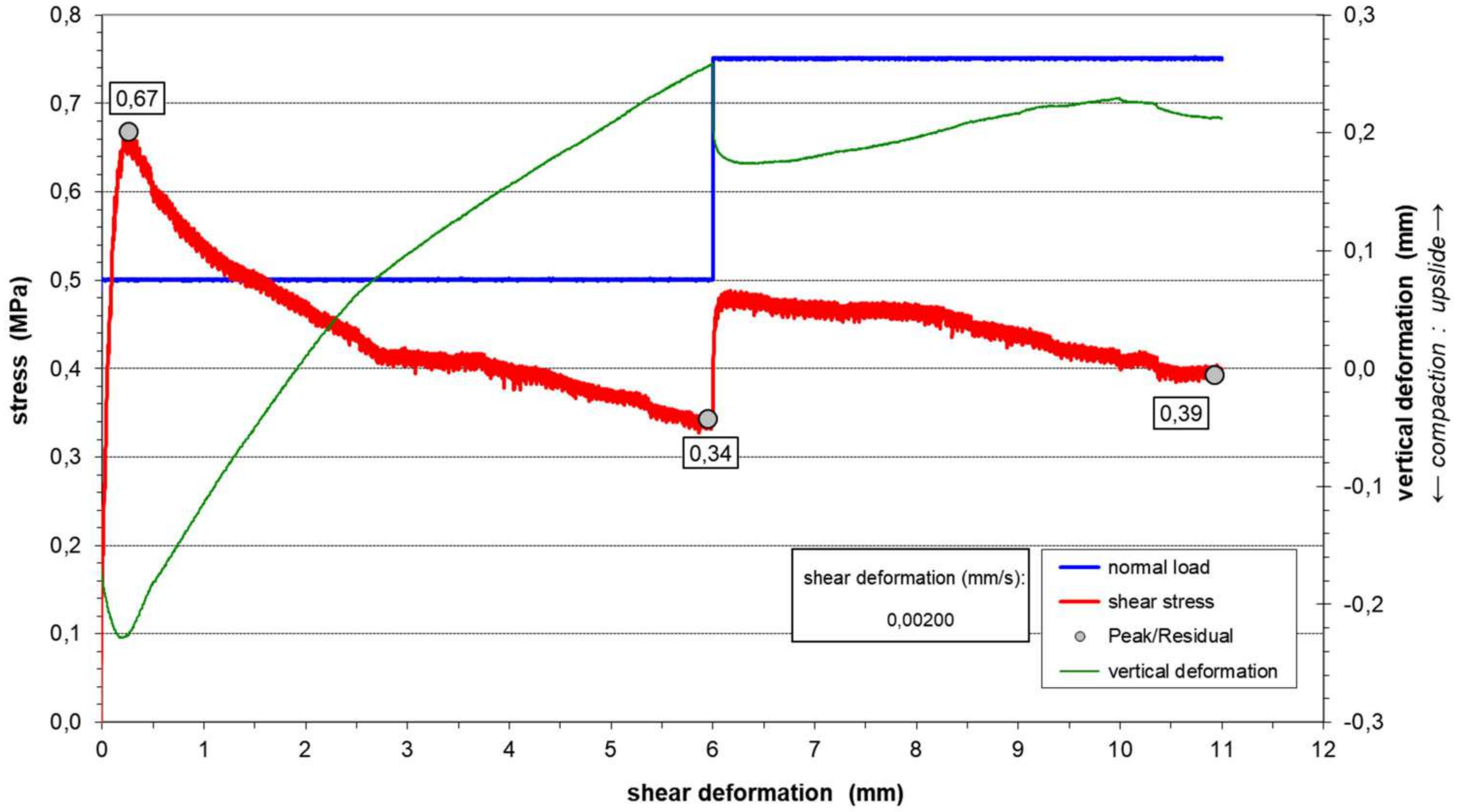
Direct shear tests (DST)

Unit – TMS (Tabuleiro)

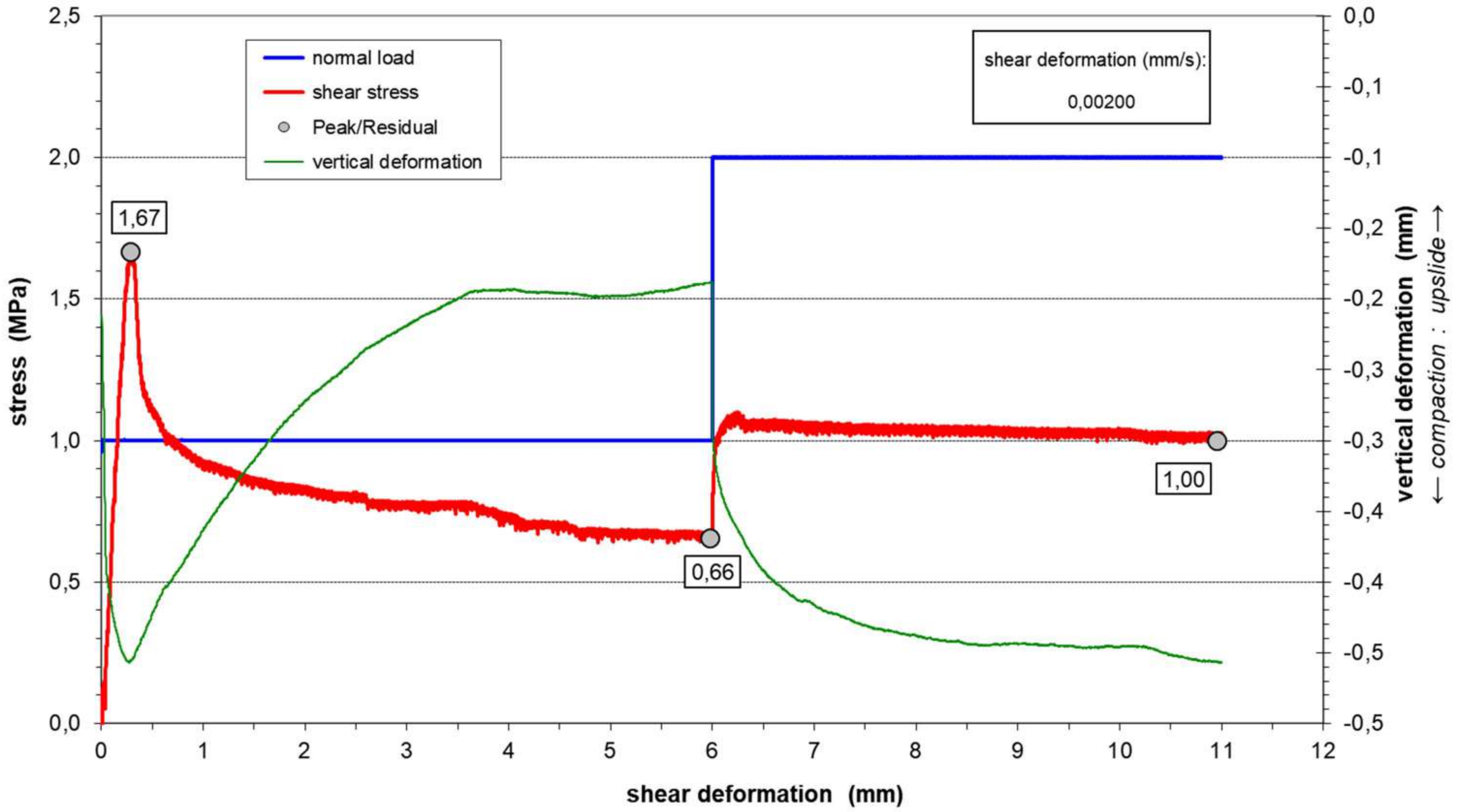
→ peak and residual strength values

Appendix 162

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



0,67
0,34
0,39
stress (MPa)
vertical deformation (mm)
← compaction : upslide →
shear deformation (mm)
shear deformation (mm/s):
0,00200
normal load
shear stress
Peak/Residual
vertical deformation



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

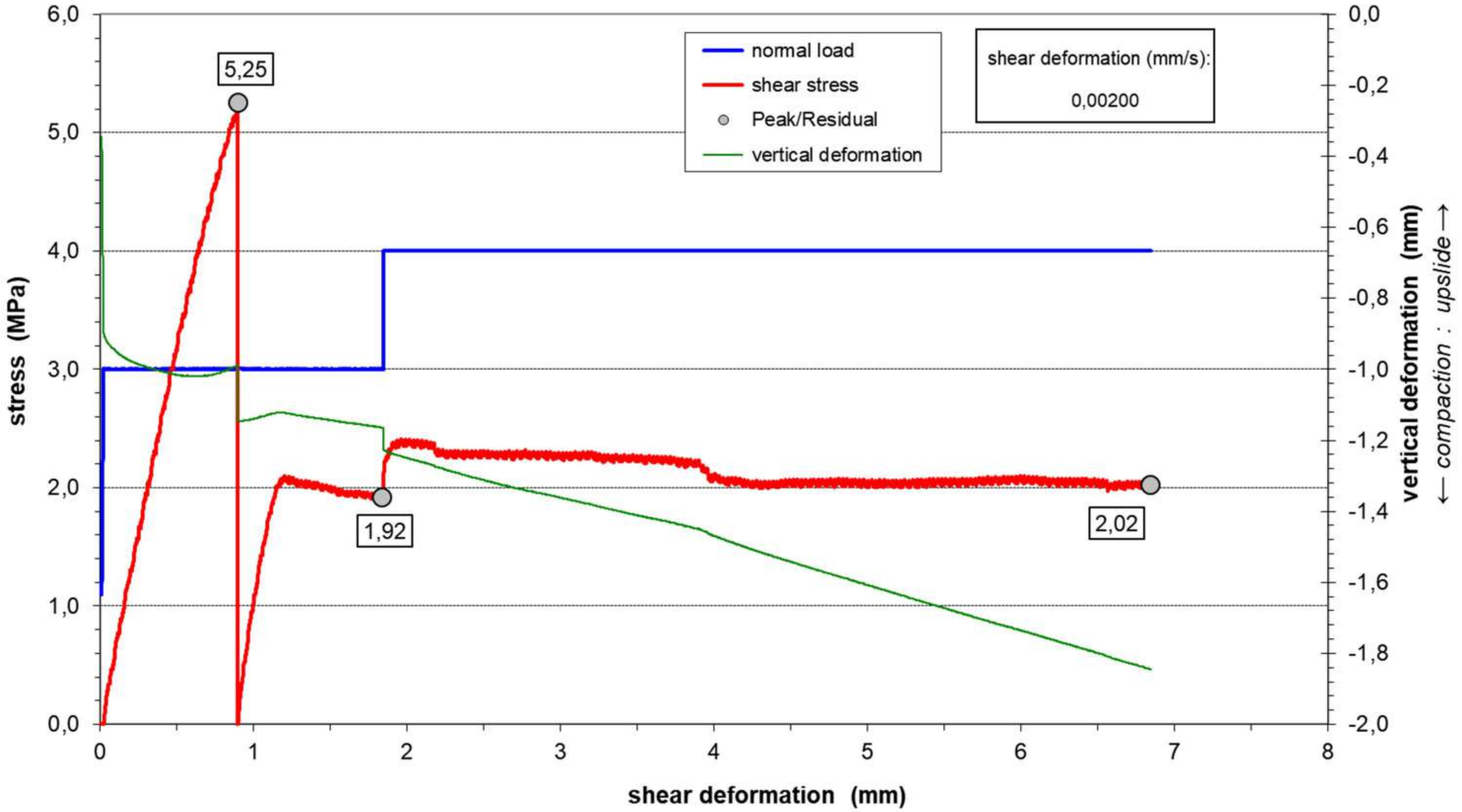
Direct shear test (DST)

Unit – TMS (Tabuleiro)

743/TMS026/SV2

Appendix 164

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

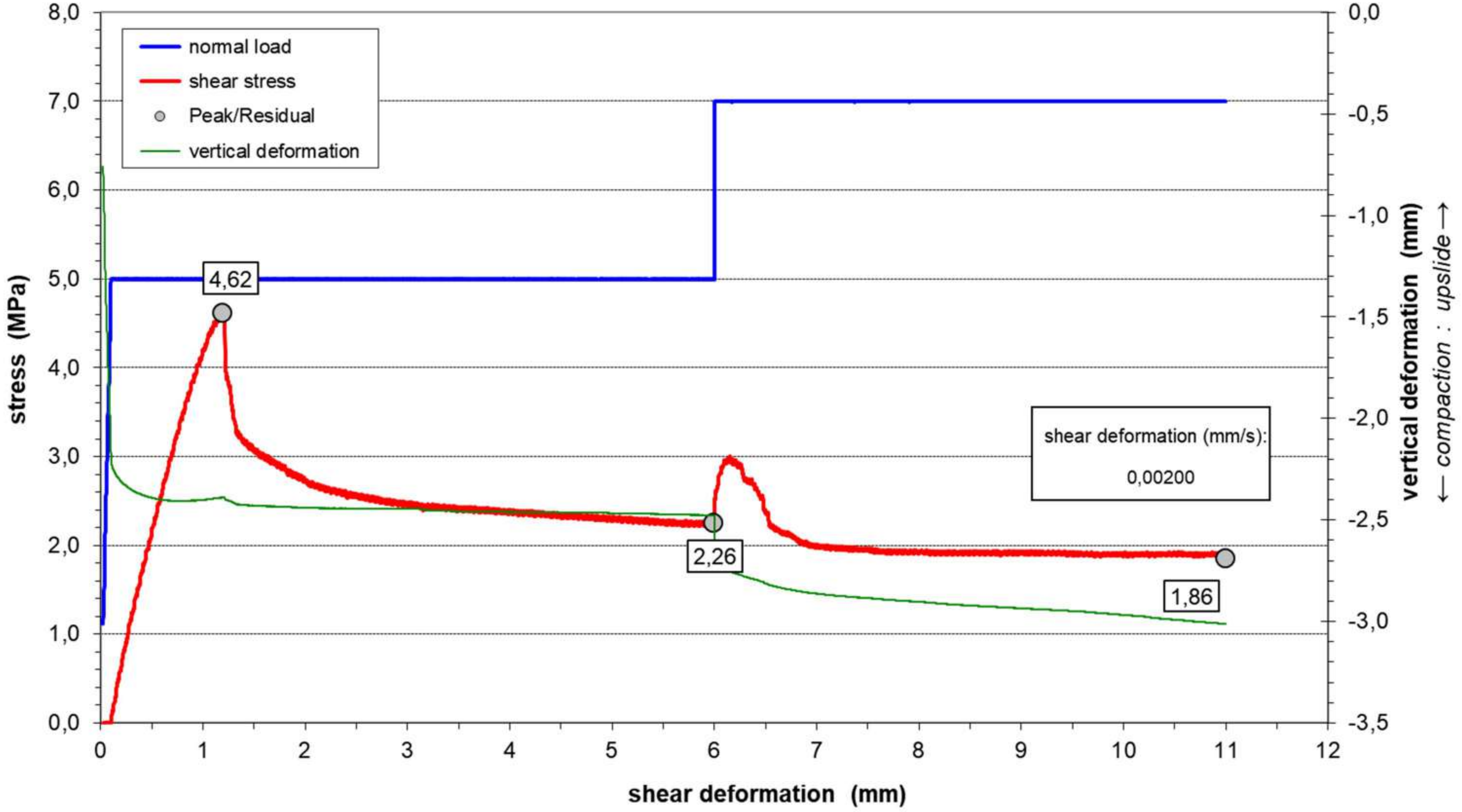
Direct shear test (DST)

Unit – TMS (Tabuleiro)

743/TMS012/SV3

Appendix 165

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

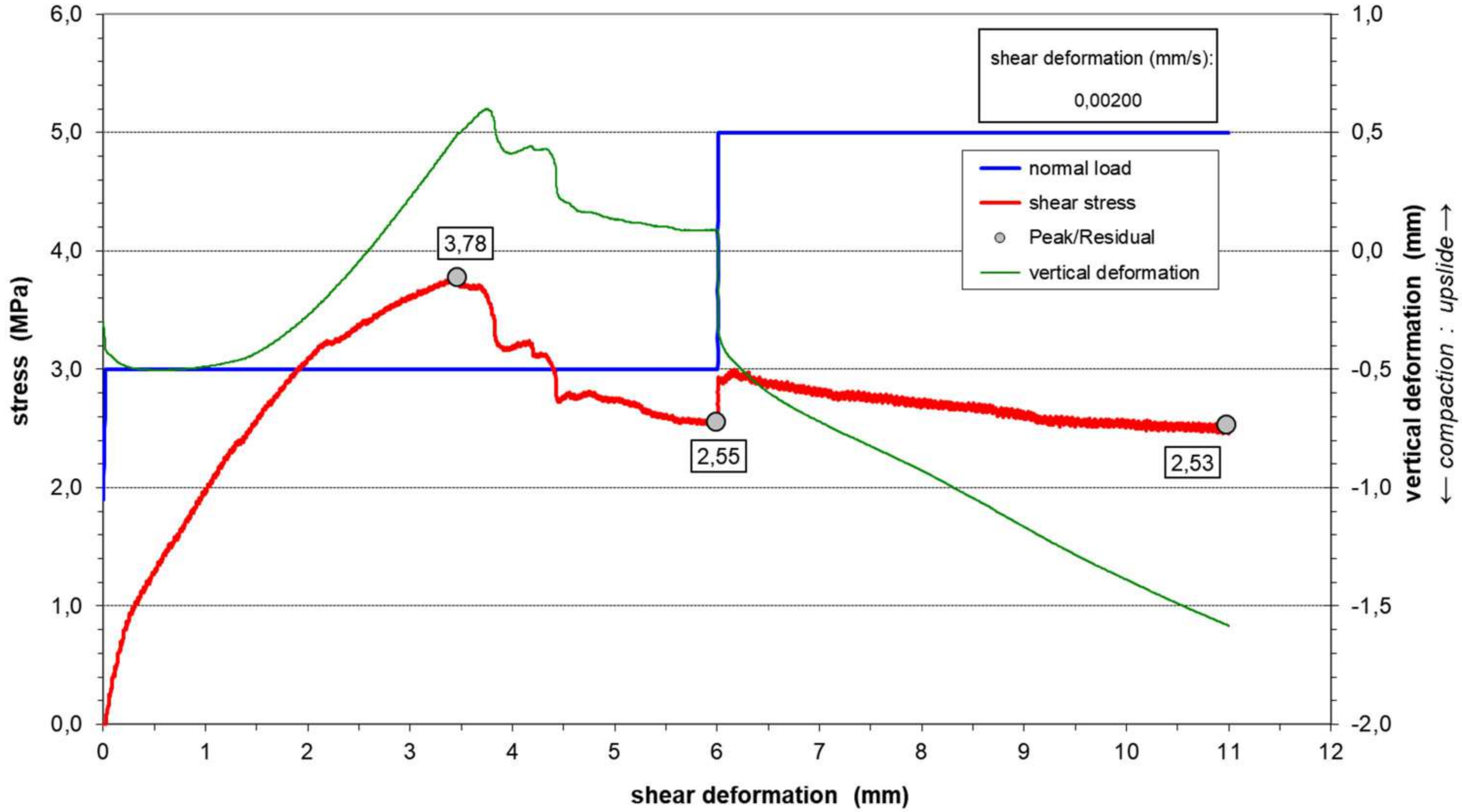
Direct shear test (DST)

Unit – TMS (Tabuleiro)

743/TMS064/SV4

Appendix 166

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

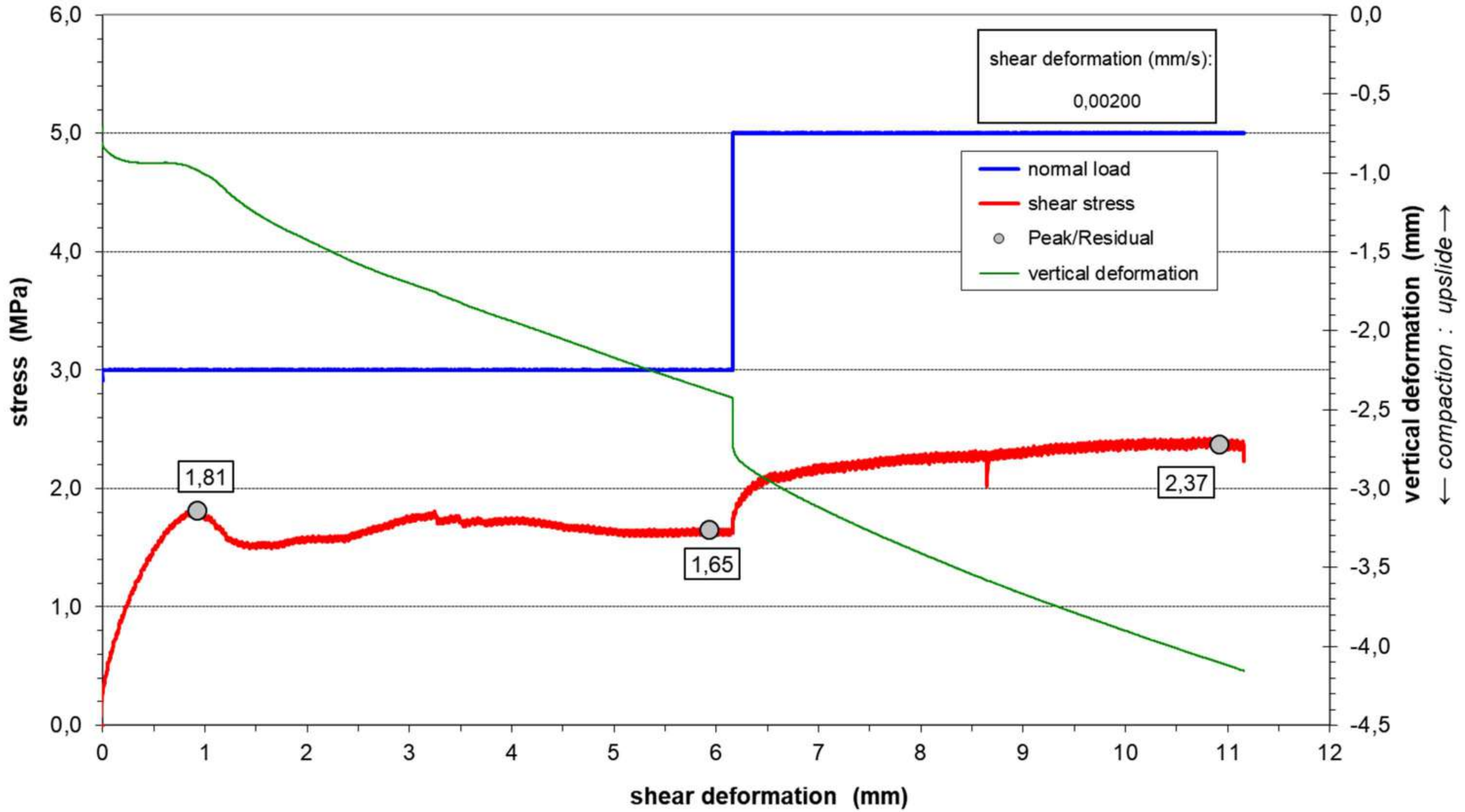
Direct shear test (DST)

Unit – TMS (Tabuleiro)

743/TMS101/SV5

Appendix 167

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Direct shear test (DST)

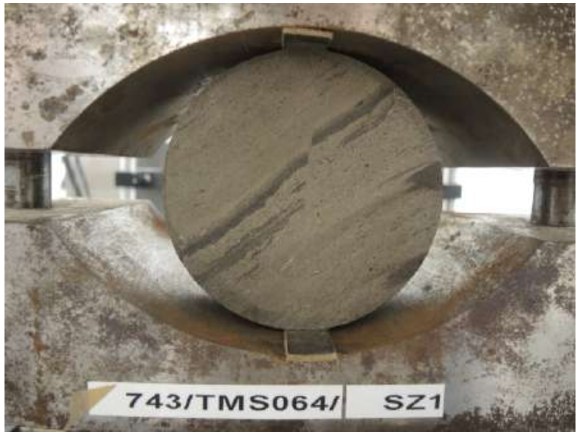
Unit – TMS (Tabuleiro)

743/TMS120/SV6

Appendix 168

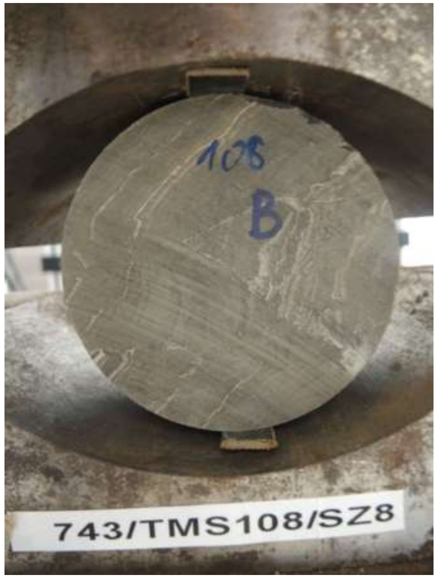
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:



AFTER:

BEFORE:

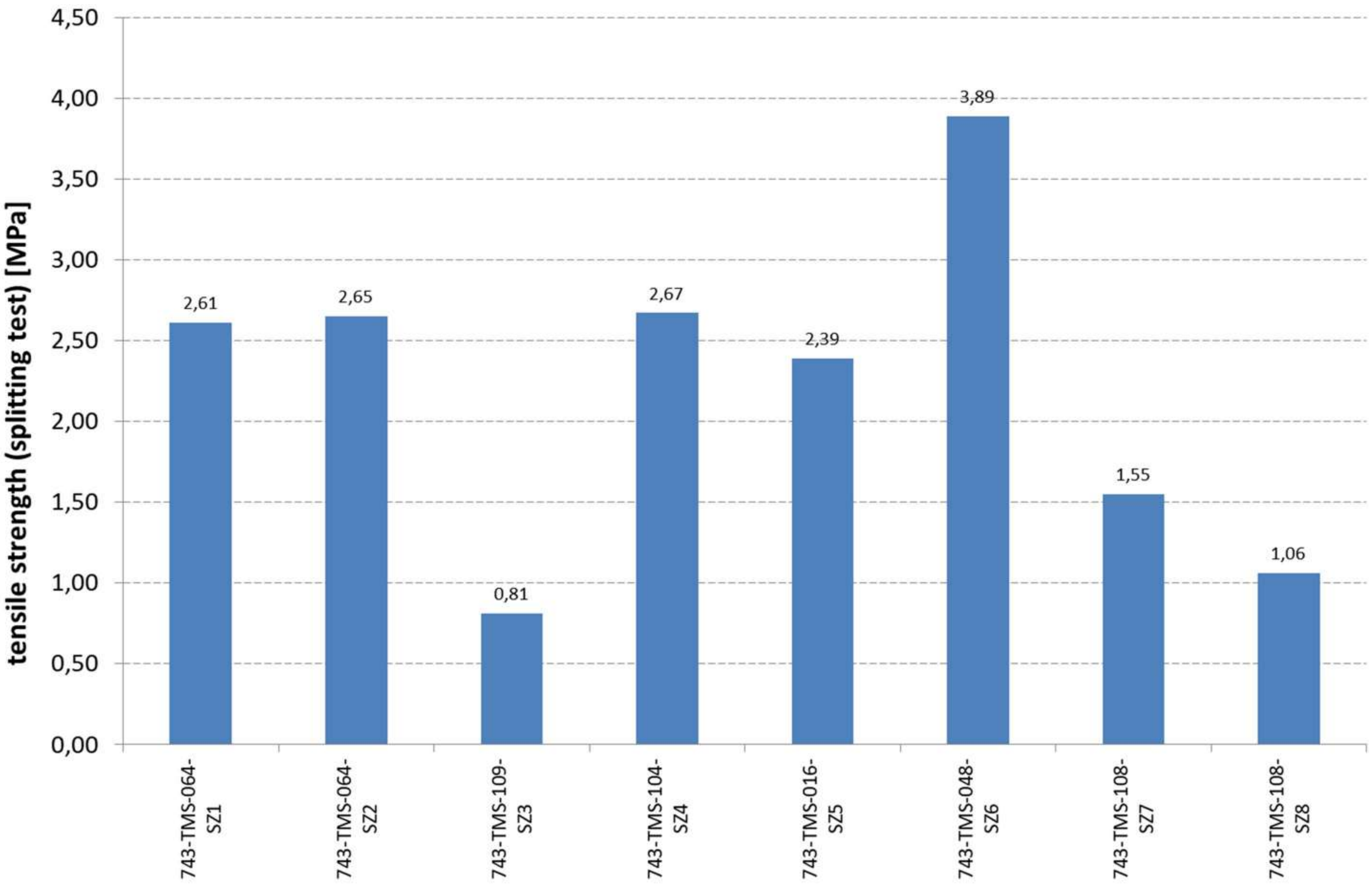


AFTER:

Samples for BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

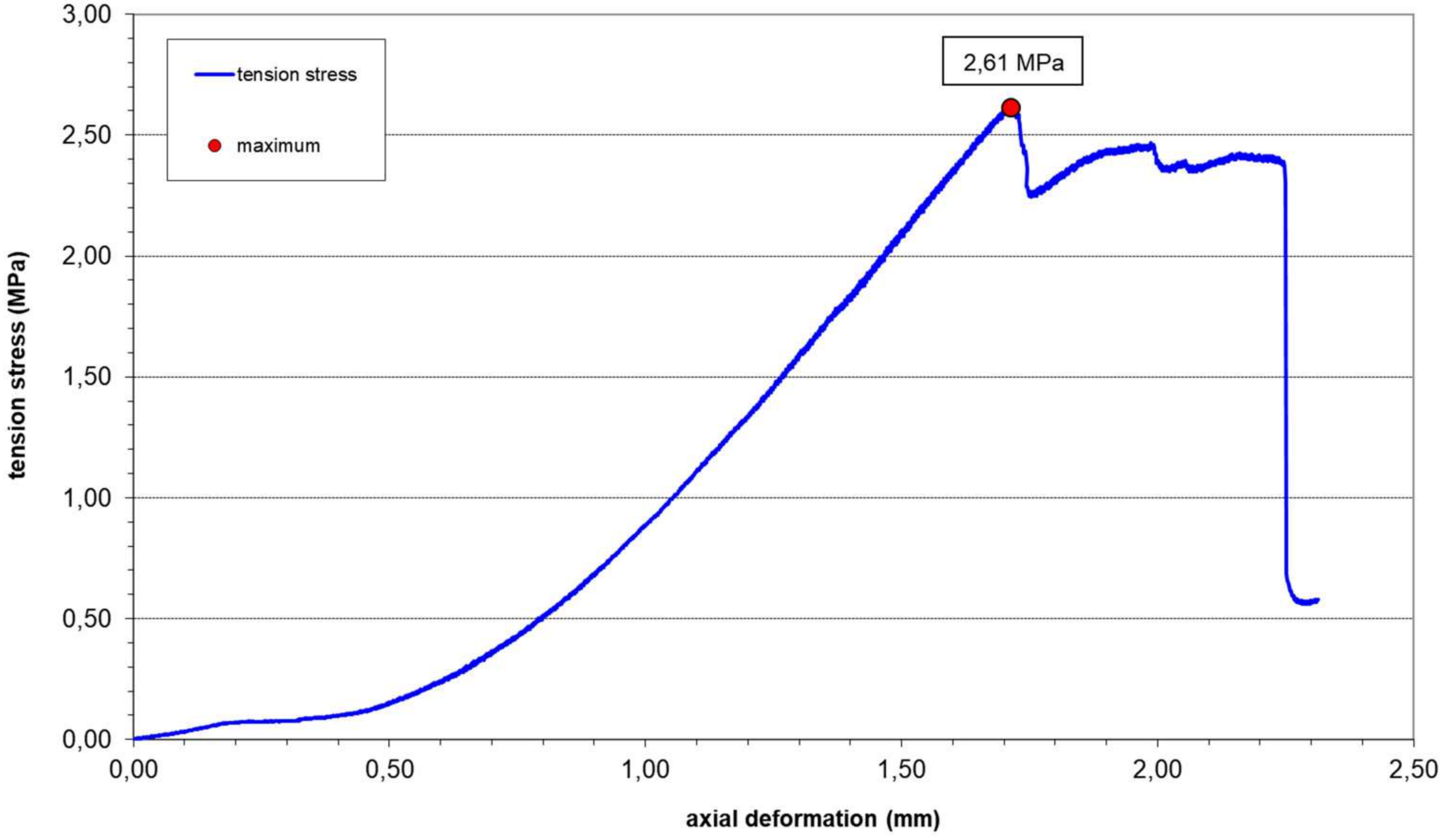
→ photo-documentation before and after the test



BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

→ maximum tensile strength values



INSTITUT FÜR GEBIRGSMECHANIK GMBH

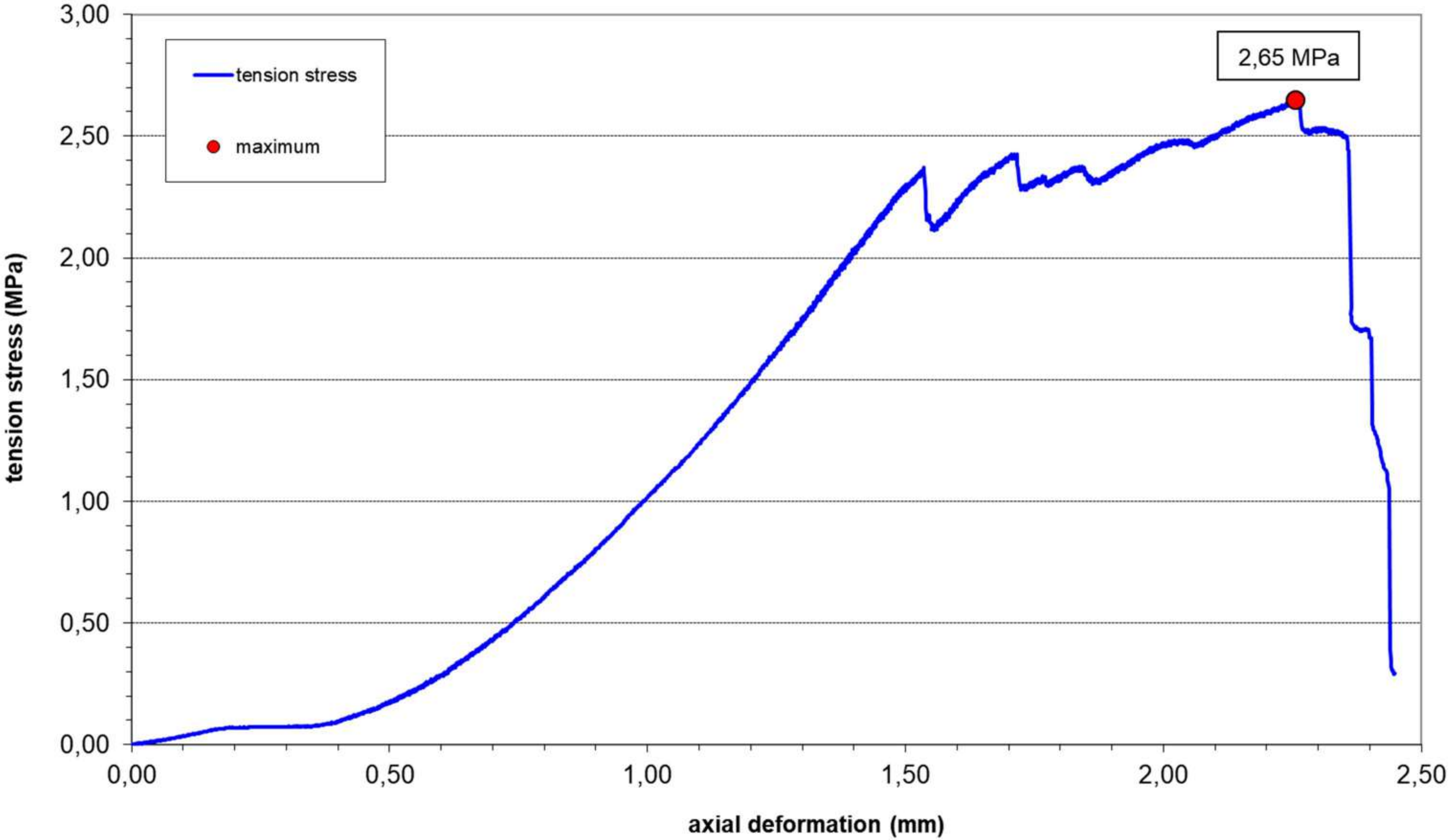
BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

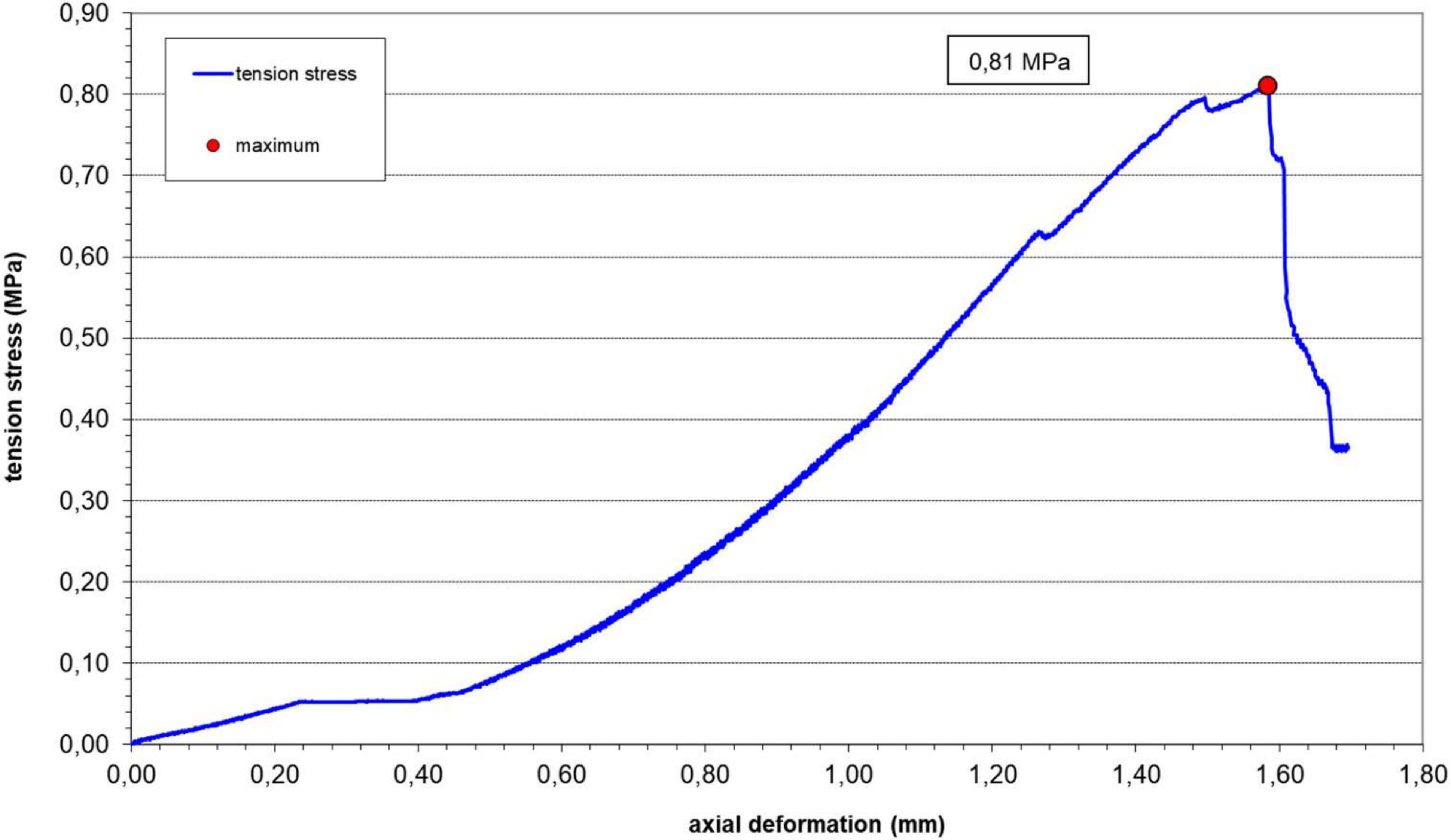
743/TMS064/SZ1

Appendix 172

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



3,00
2,50
2,00
1,50
1,00
0,50
0,00
tension stress (MPa)
tension stress
maximum
2,65 MPa
0,00
0,50
1,00
1,50
2,00
2,50
axial deformation (mm)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

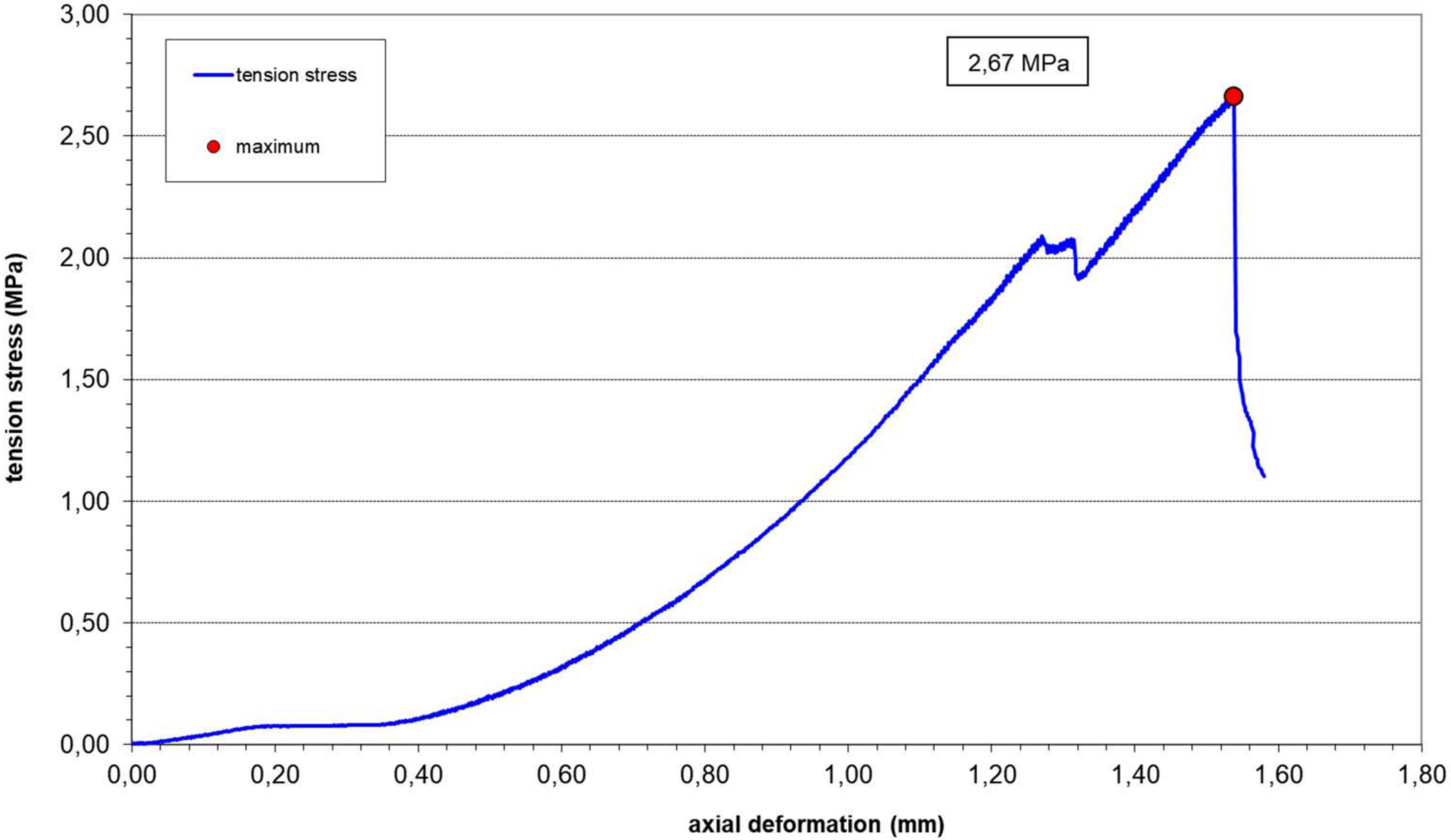
BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

743/TMS109/SZ3

Appendix 174

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

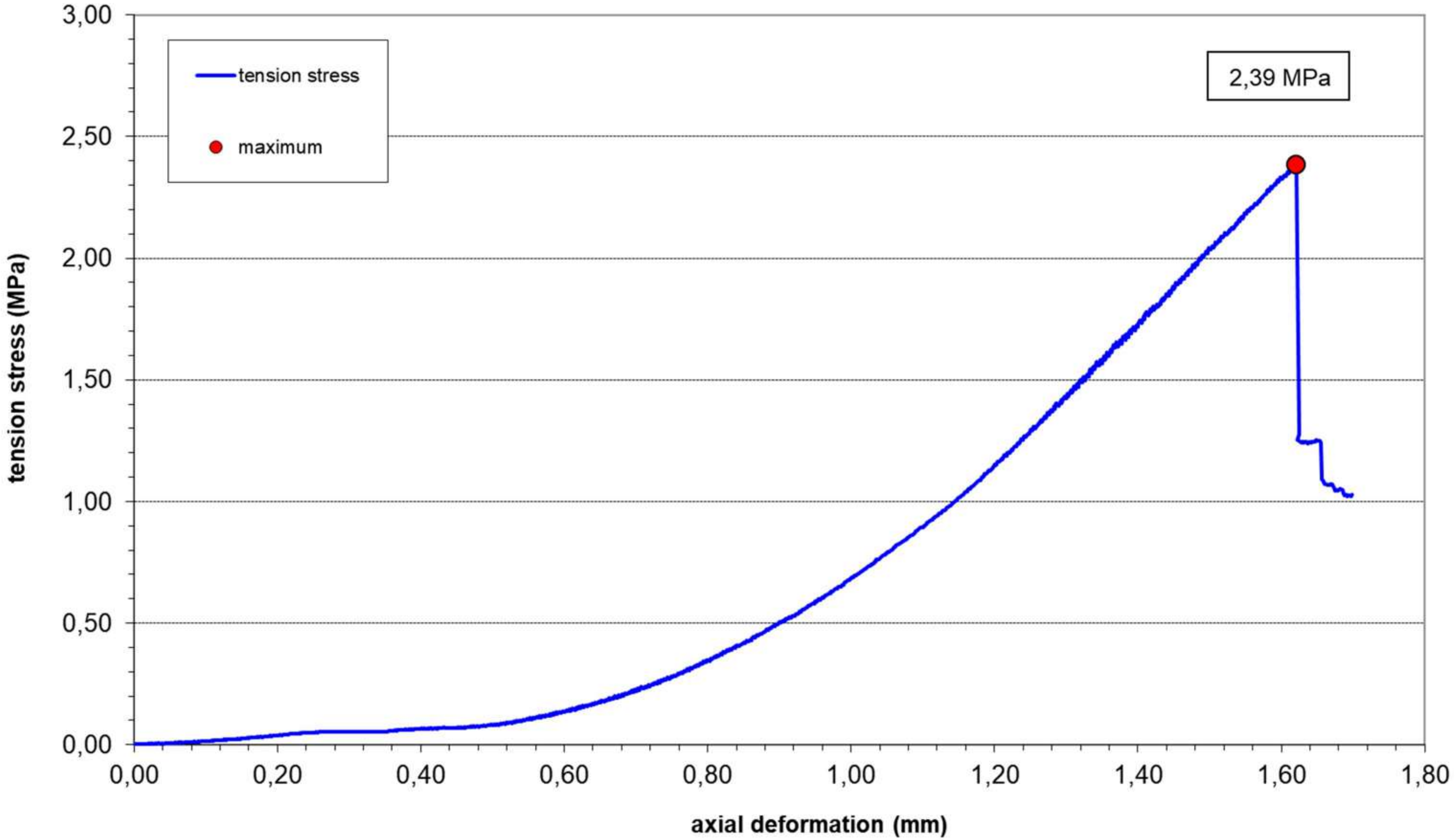
BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

743/TMS104/SZ4

Appendix 175

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

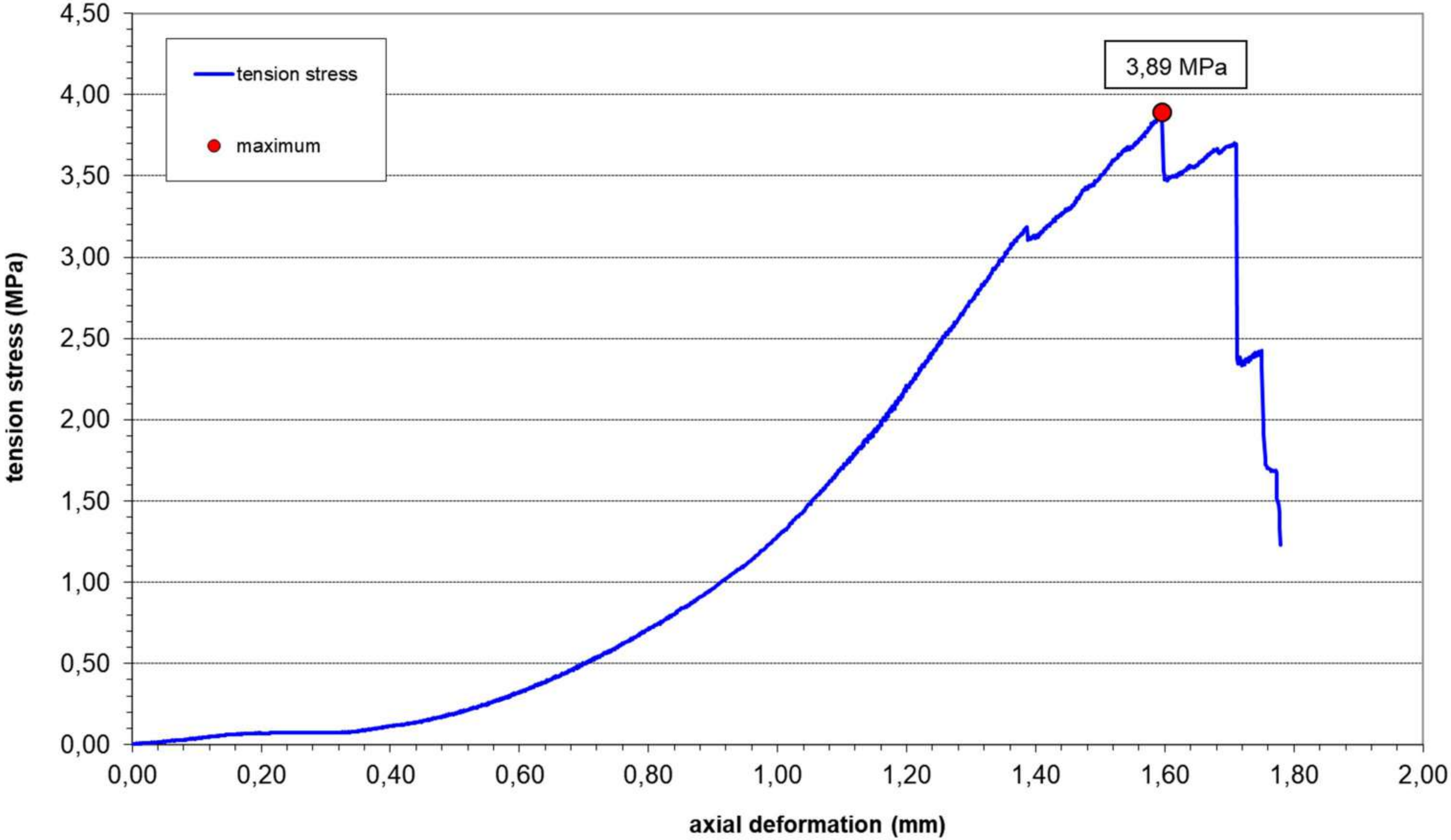
BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

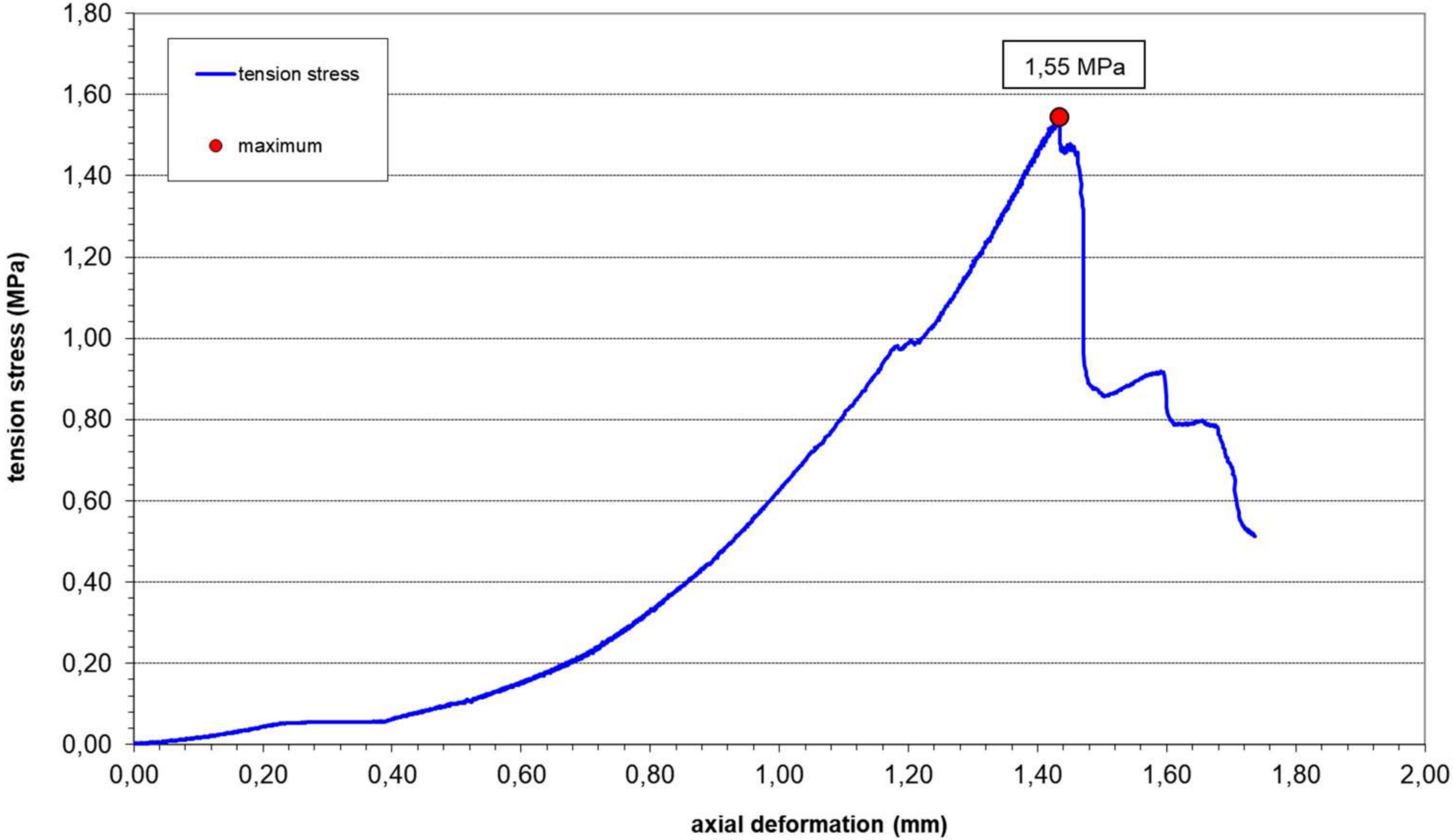
743/TMS016/SZ5

Appendix 176

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



tension stress
maximum
3,89 MPa
4,50
4,00
3,50
3,00
2,50
2,00
1,50
1,00
0,50
0,00
tension stress (MPa)
0,00
0,20
0,40
0,60
0,80
1,00
1,20
1,40
1,60
1,80
2,00
axial deformation (mm)



INSTITUT FÜR GEBIRGSMECHANIK GMBH

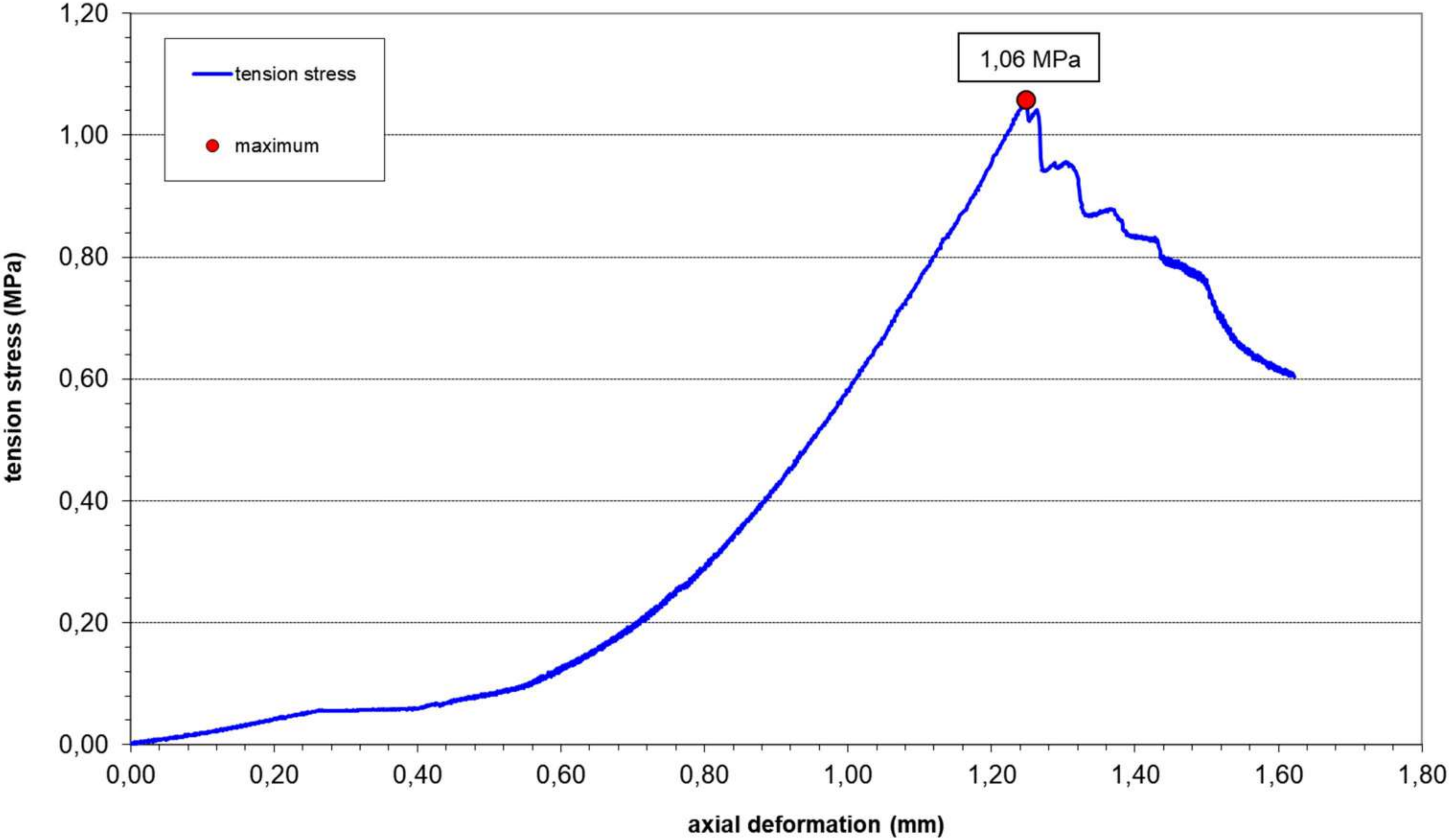
BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

743/TMS108/SZ7

Appendix 178

B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”



INSTITUT FÜR GEBIRGSMECHANIK GMBH

BRAZIL tests (splitting tension tests)

Unit – TMS (Tabuleiro)

743/TMS108/SZ8

Appendix 179

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:

AFTER:

INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

Samples for direct tensile strength tests (DTT)

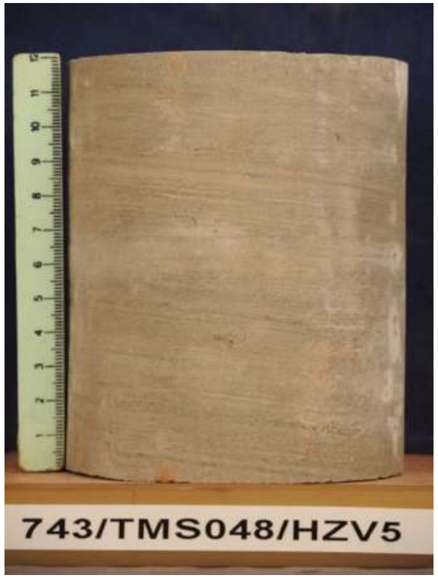
Unit – TMS (Tabuleiro)

→ photo-documentation before and after the test

Appendix 180

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:



AFTER:

failed just before testing

INSTITUT FÜR GEBIRGSMECHANIK GMBH

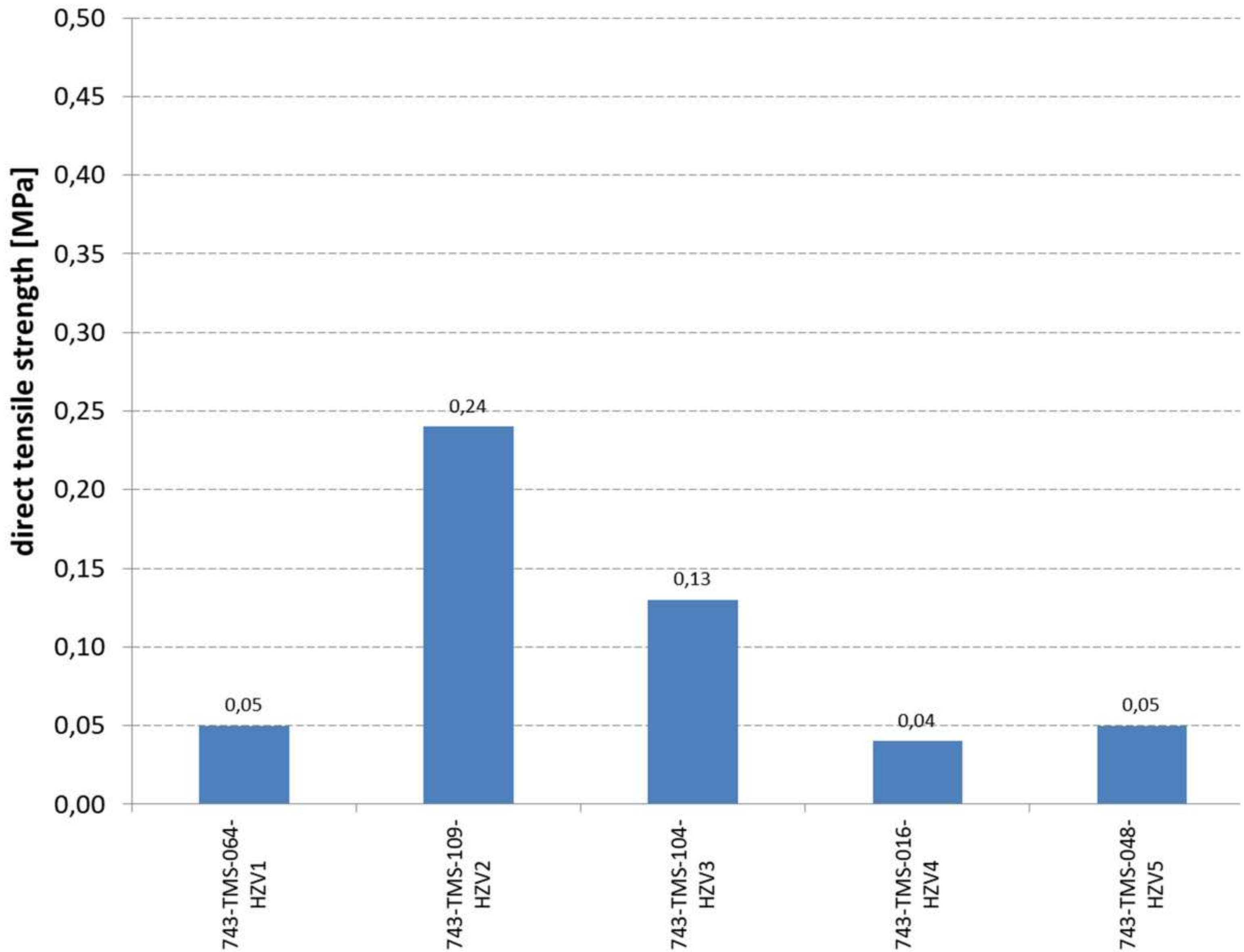
Samples for direct tensile strength tests (DTT)

Unit – TMS (Tabuleiro)

→ photo-documentation before and after the test

Appendix 181

B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”



INSTITUT FÜR GEBIRGSMECHANIK GMBH

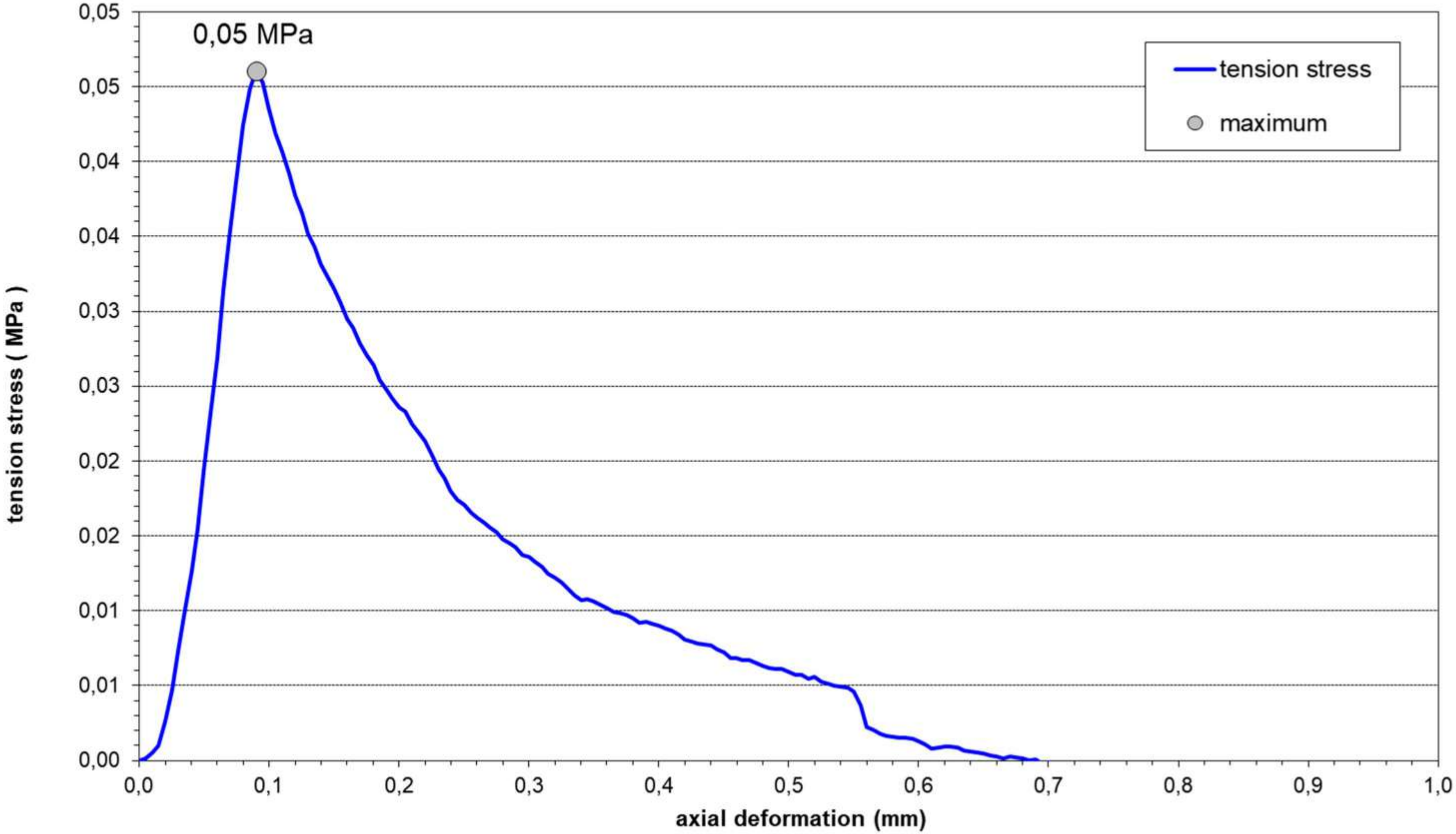
Direct tensile strength tests (DTT)

Unit – TMS (Tabuleiro)

→ maximum tensile strength values

Appendix 182

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

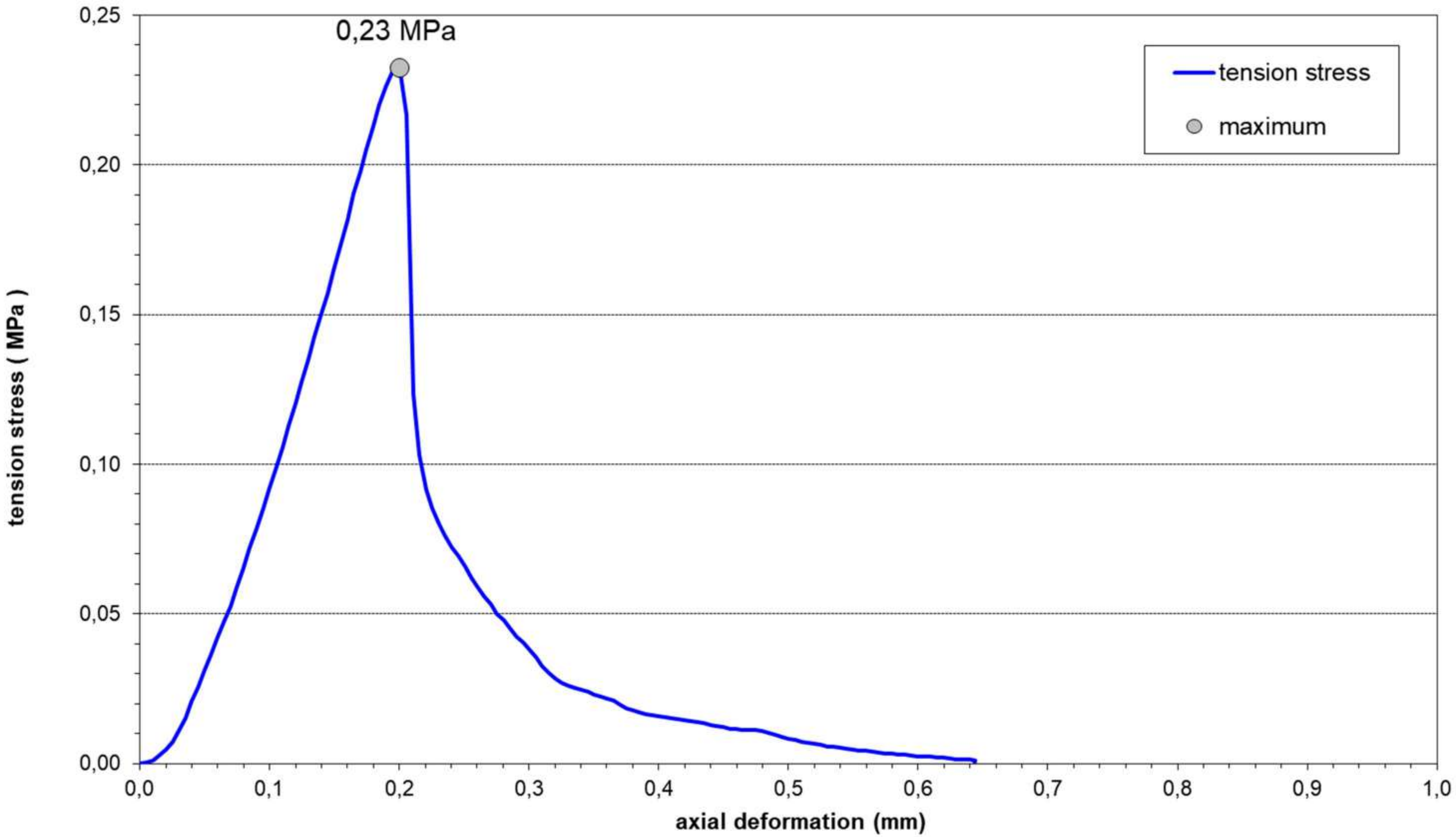
direct tensile strength test (DTT)

Unit – TMS (Tabuleiro)

743/TMS064/HZV1

Appendix 183

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

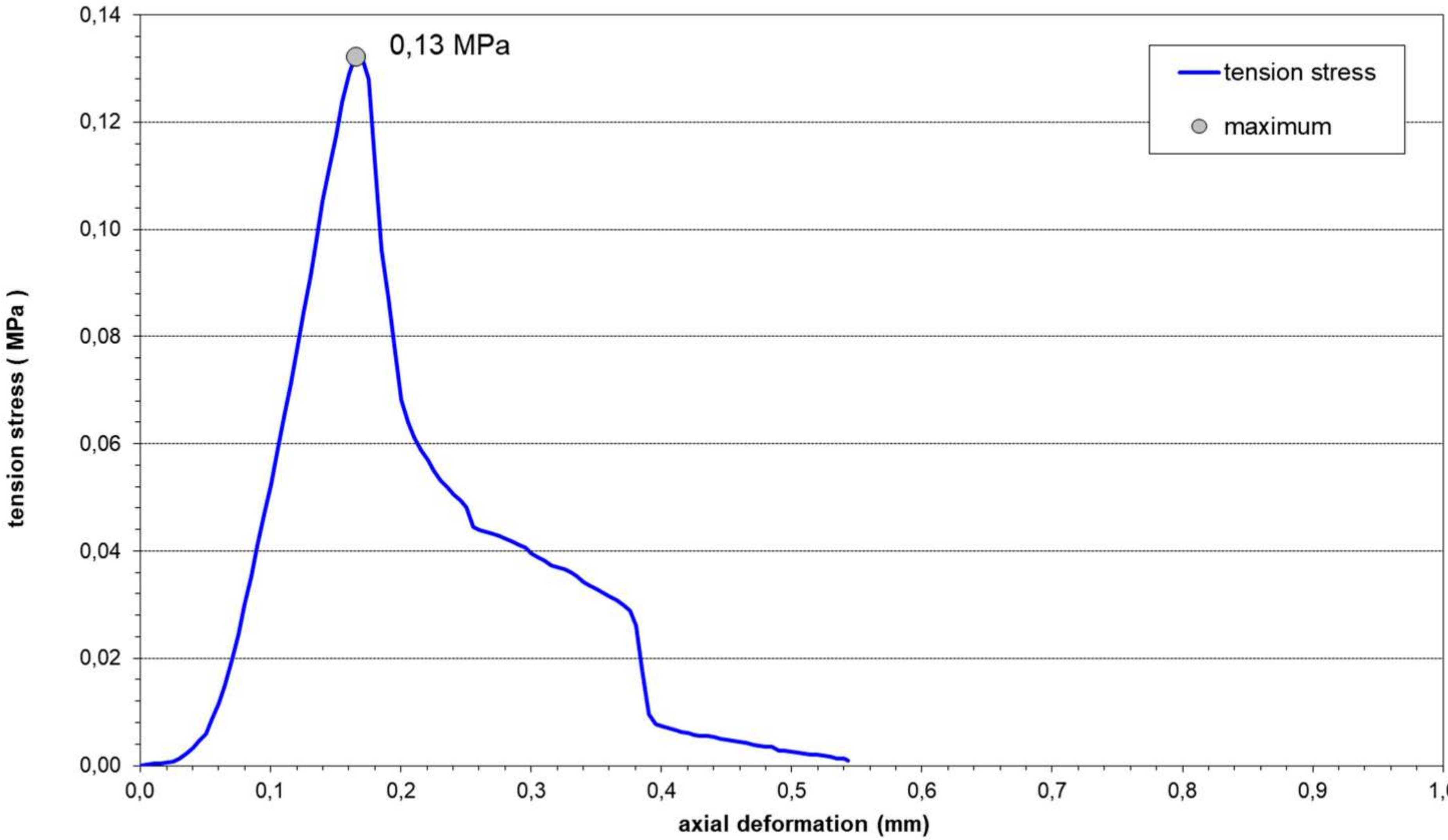
direct tensile strength test (DTT)

Unit – TMS (Tabuleiro)

743/TMS109/HZV2

Appendix 184

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

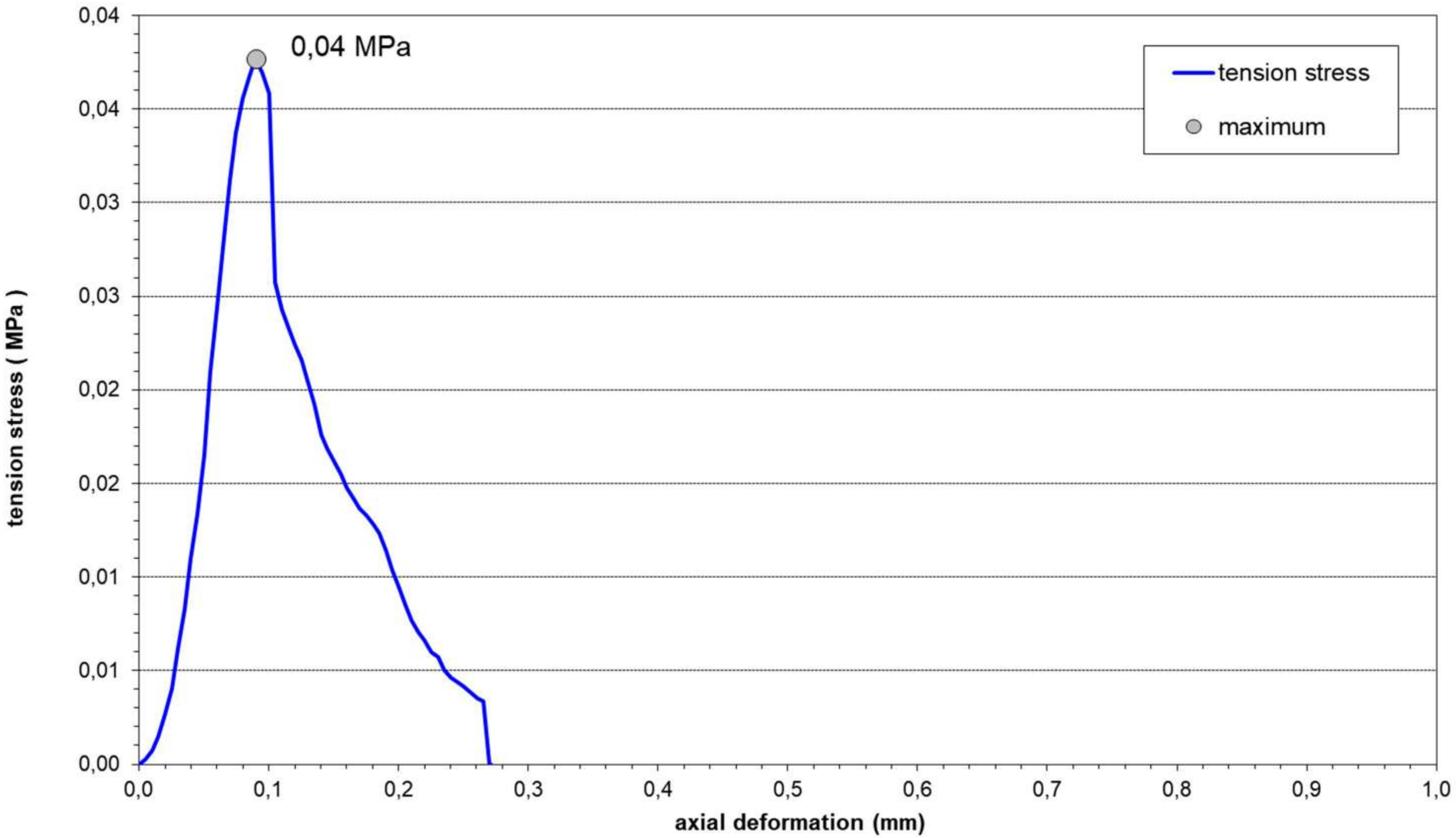
direct tensile strength test (DTT)

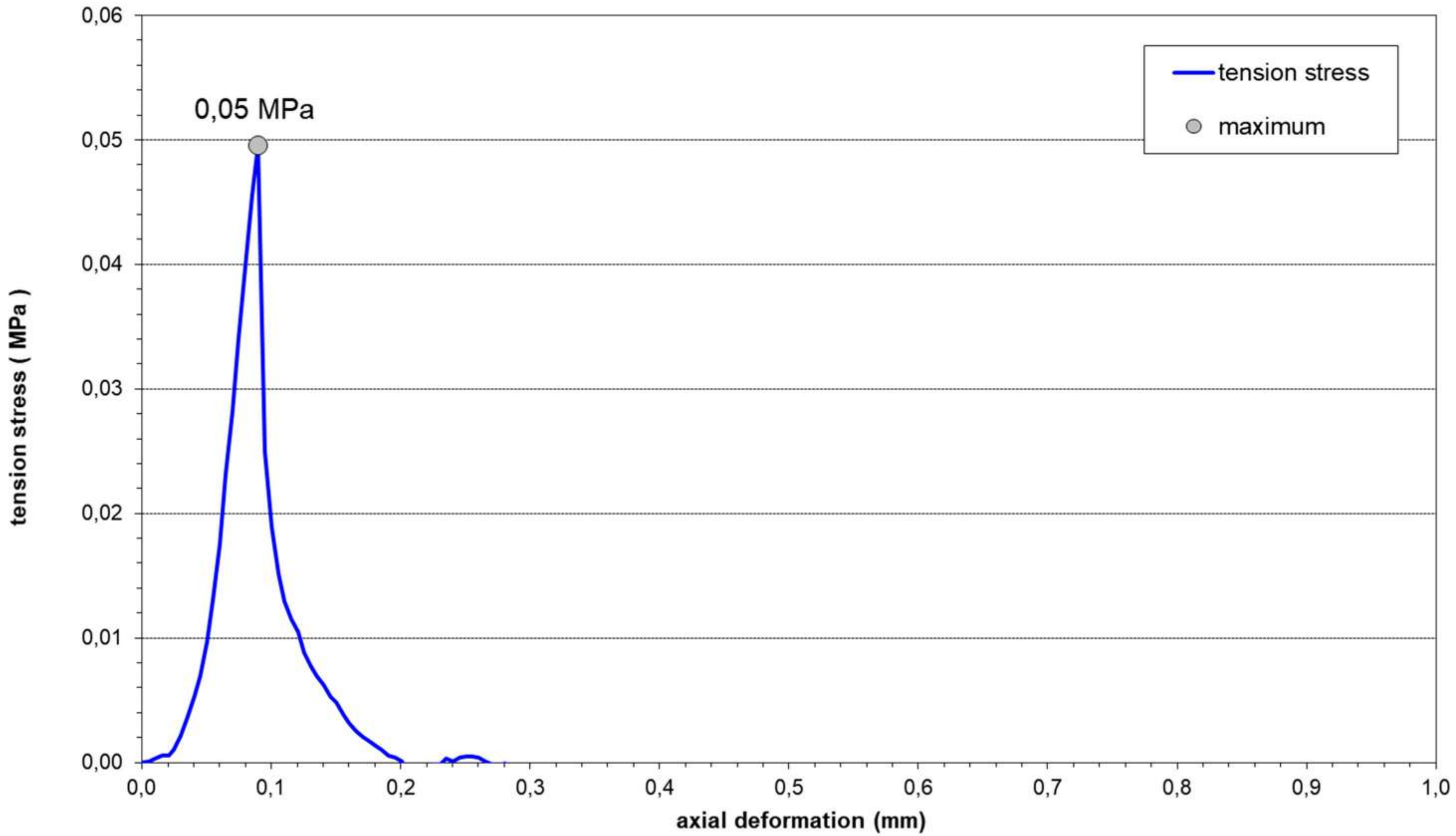
Unit – TMS (Tabuleiro)

743/TMS104/HZV3

Appendix 185

B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”


0,04 MPa
tension stress
maximum
tension stress (MPa)
0,04
0,04
0,03
0,03
0,02
0,02
0,01
0,01
0,00
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
axial deformation (mm)



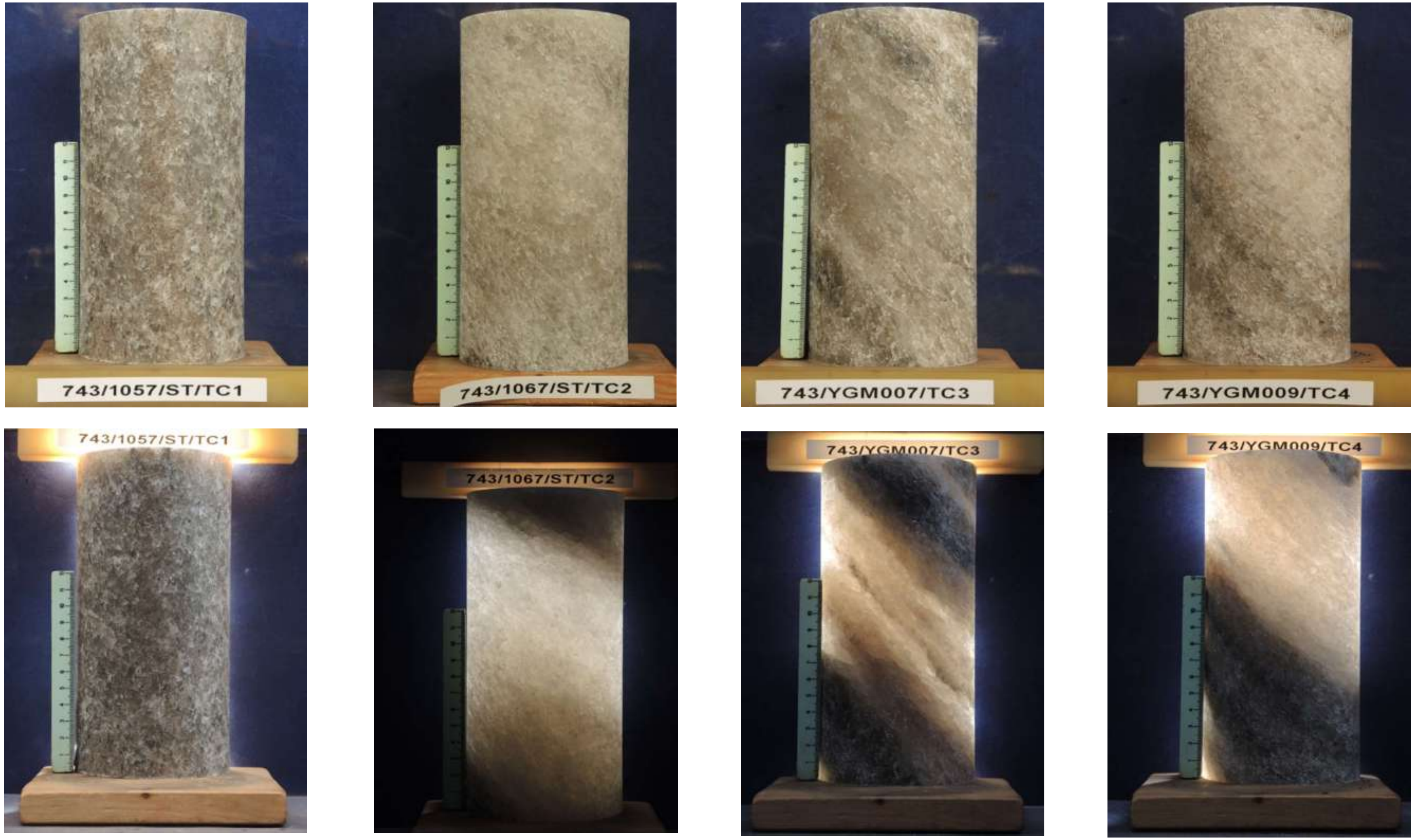
INSTITUT FÜR **GEBIRGSMECHANIK** GMBH	**direct tensile strength test (DTT)** **Unit – TMS (Tabuleiro)** 743/TMS048/HZV5	**Appendix 187** ***B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"***

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	**7**						**8**
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	6		5		6		

IfG - Lab-No.	743/HAL/YGM004/ TC_d1	743/HAL/YGM008/ TC_d2	743/HAL/YGM007/ TC3	743/HAL/YGM009/ TC4	743/HAL/YGM010/ TC5	743/HAL/YGM011/ TC6	743/HAL/YGM012/ TC7
Rock Type / Unit	**HAL**	**HAL**	**HAL**	**HAL**	**HAL**	**HAL**	**HAL**
Sample	**YGM_004**	**YGM008**	**YGM007**	**YGM009**	**YGM010**	**YGM011**	**YGM012**
Depth (m)							
Length l (mm) =	192.445	192.415	192.315	192.493	192.410	192.385	192.380
Diameter d (mm) =	96.440	96.375	96.535	96.448	96.570	96.655	96.570
Ratio l_o/d_o =	2.00	2.00	1.99	2.00	1.99	1.99	1.99
Mass M (g) =	3018.50	3019.6	3016.3	3009.9	3024.4	3029.0	3016.5
Area A (cm^2) =	73.047	72.949	73.191	73.059	73.244	73.373	73.244
Volume V (cm^3) =	1405.76	1403.65	1407.58	1406.34	1409.30	1411.59	1409.08
Density ρ (g/cm^3) =	2.147	2.151	2.143	2.140	2.146	2.146	2.141
US L (h) - p	45.62						
US Q1 (a/c) - p	21.51		21.80	22.93	21.54	22.13	21.84
US Q2 (b/d) - p	22.06	21.82	21.87		22.47	22.62	21.85
US L (h) - s	77.37						
US L (h) - p(s)							
$V_{p\text{-axial}}$ (km/s) =	4.22	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
$V_{p\text{-radial: a-c}}$ (km/s) =	4.48	#DIV/0!	4.43	4.21	4.48	4.37	4.42
$V_{p\text{-radial: b-d}}$ (km/s) =	4.37	4.42	4.41	#DIV/0!	4.30	4.27	4.42
$V_{s\text{-axial}}$ (km/s) =	2.49	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
elast. constants from ultrasonic survey:							
E_d (GPa) =	32.77	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
K_d (GPa) =	20.50	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
G_d (GPa) =	13.28	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
ν_d =	0.234	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
strength & deformation behavior (experimental results)							
	TC	**TC**	**TC**	**TC**	**TC**	**UC**	**UC**
Temp. (°C)	**23**	**57**	**57**	**57**	**57**	**57**	**90**
σ_3 (MPa) =	1.0	1.0	0.2	0.5	3.0	5.0	1.0
σ_{Dil} (MPa) =	9.8	7.3	4.6	6.2	16.8	35.9	7.2
ΔV_{Dil} (%) =	-0.03	-0.03	-0.02	-0.03	-0.04	-0.31	0.00
ε_{Dil} (%) =	0.08	0.09	0.06	0.08	0.81	11.66	0.09
σ_{Fail} (MPa) =	32.2	28.7	20.9	23.9	36.3	40.5	20.9
ΔV_{Fail} (%) =	3.04	2.02	1.63	1.69	1.43	-0.09	2.00
ε_{Fail} (%) =	6.06	9.86	4.20	5.68	17.79	19.92	10.70
σ_{1Fail} (MPa) =	33.17	29.68	21.13	24.38	39.26	45.53	21.86

REFLECTED:

TRANSMITTED:



σ_3 = 1. Mpa T = 23°C	σ_3 = 1.0 Mpa T = 57°C	σ_3 = 0.2 Mpa T = 57°C	σ_3 = 0.5 Mpa T = 57°C

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Samples for triaxial strength tests (TC_nat)

Unit – PRP (Pure Halite)

→ photos before the test (reflected & transmitted light)

Appendix 190

B IfG 22/2021 “Rock Mechanical Investigations – Maceio – BRASKEM”

BEFORE:

AFTER:

σ_3 = 1. Mpa
T = 23°C

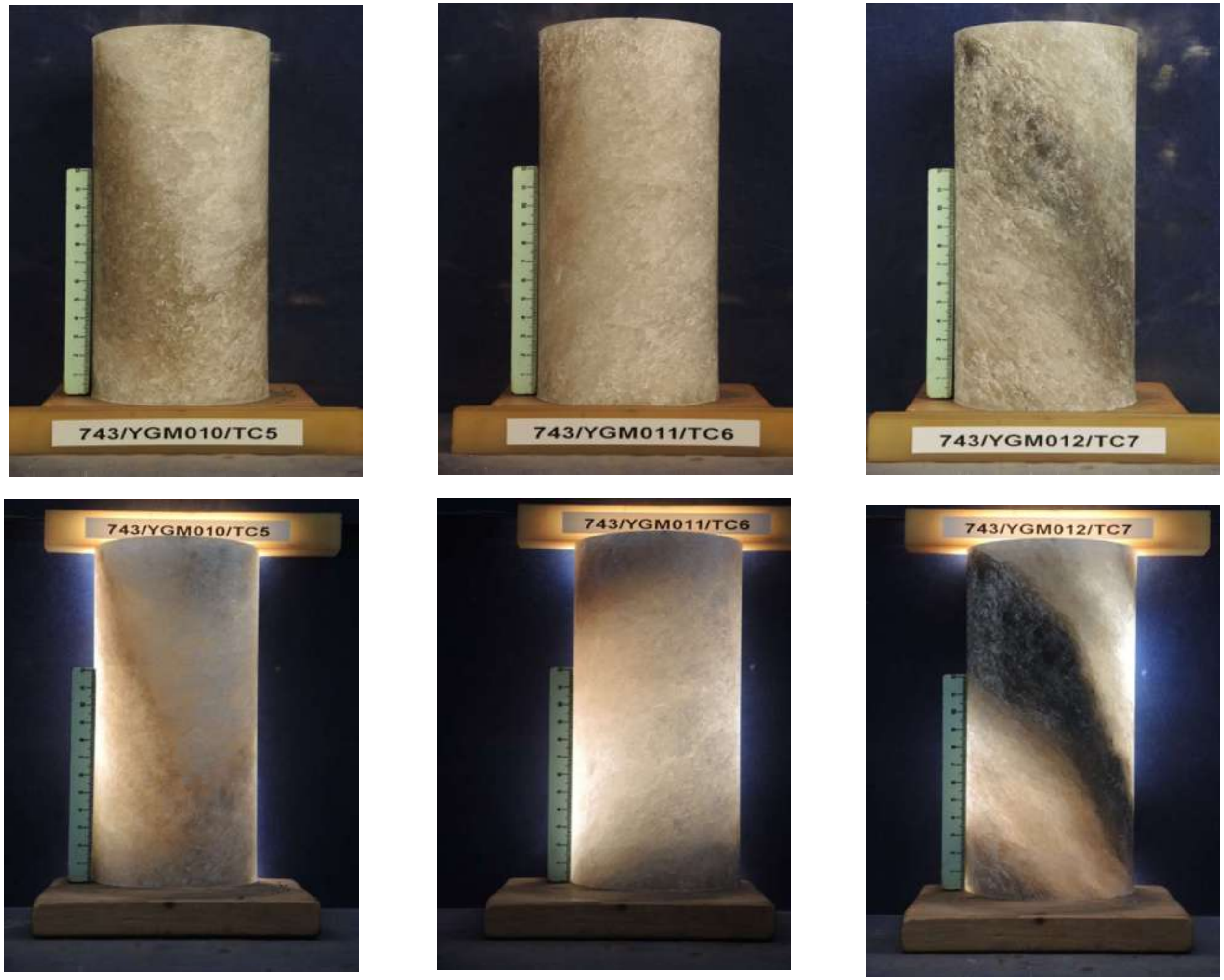
σ_3 = 1.0 Mpa
T = 57°C

σ_3 = 0.2 Mpa
T = 57°C

σ_3 = 0.5 Mpa
T = 57°C

REFLECTED:

TRANSMITTED:

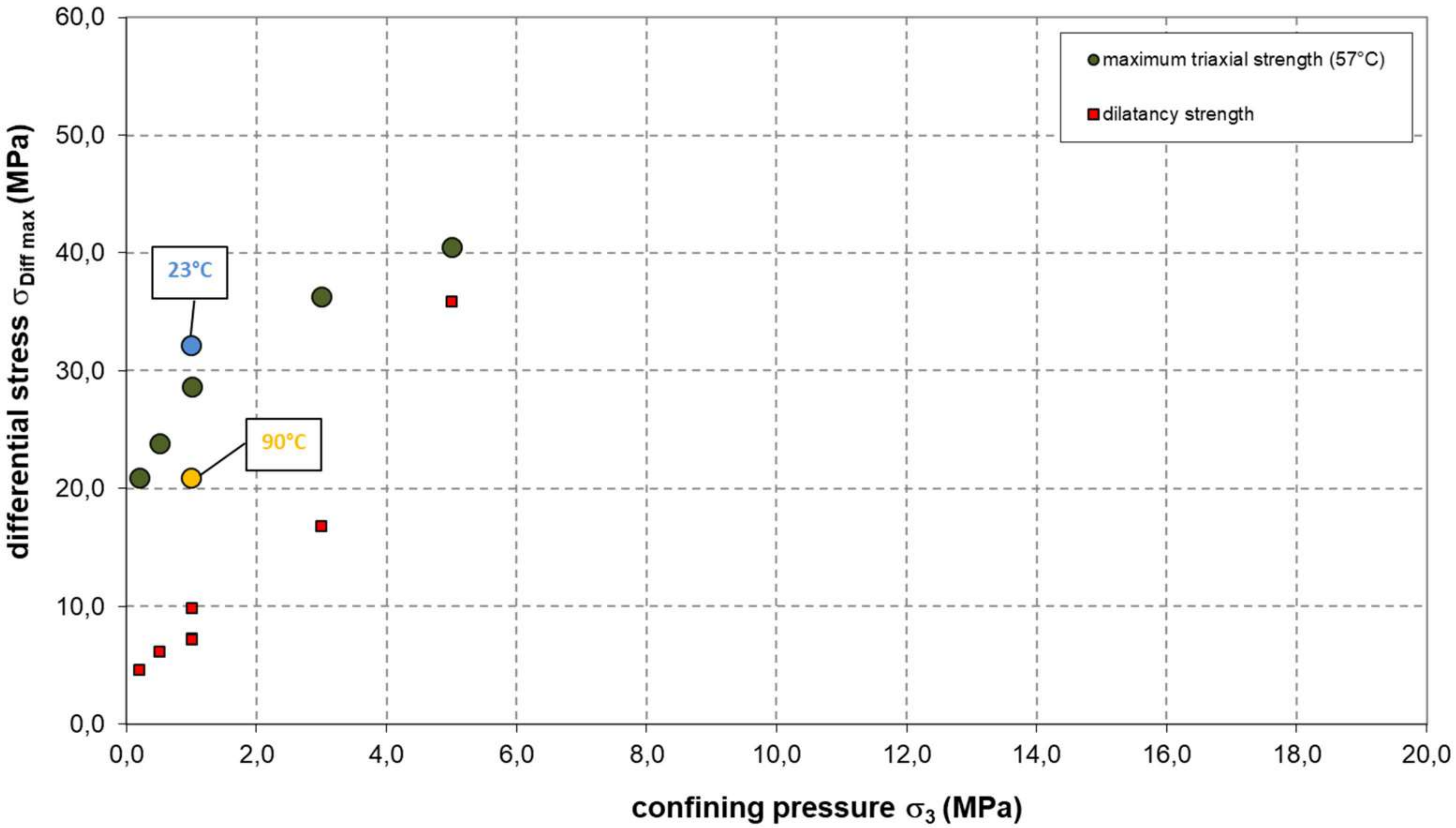


σ_3 = 3.0 MPa T = 57°C	σ_3 = 5.0 MPa T = 57°C	σ_3 = 1.0 MPa T = 90°C

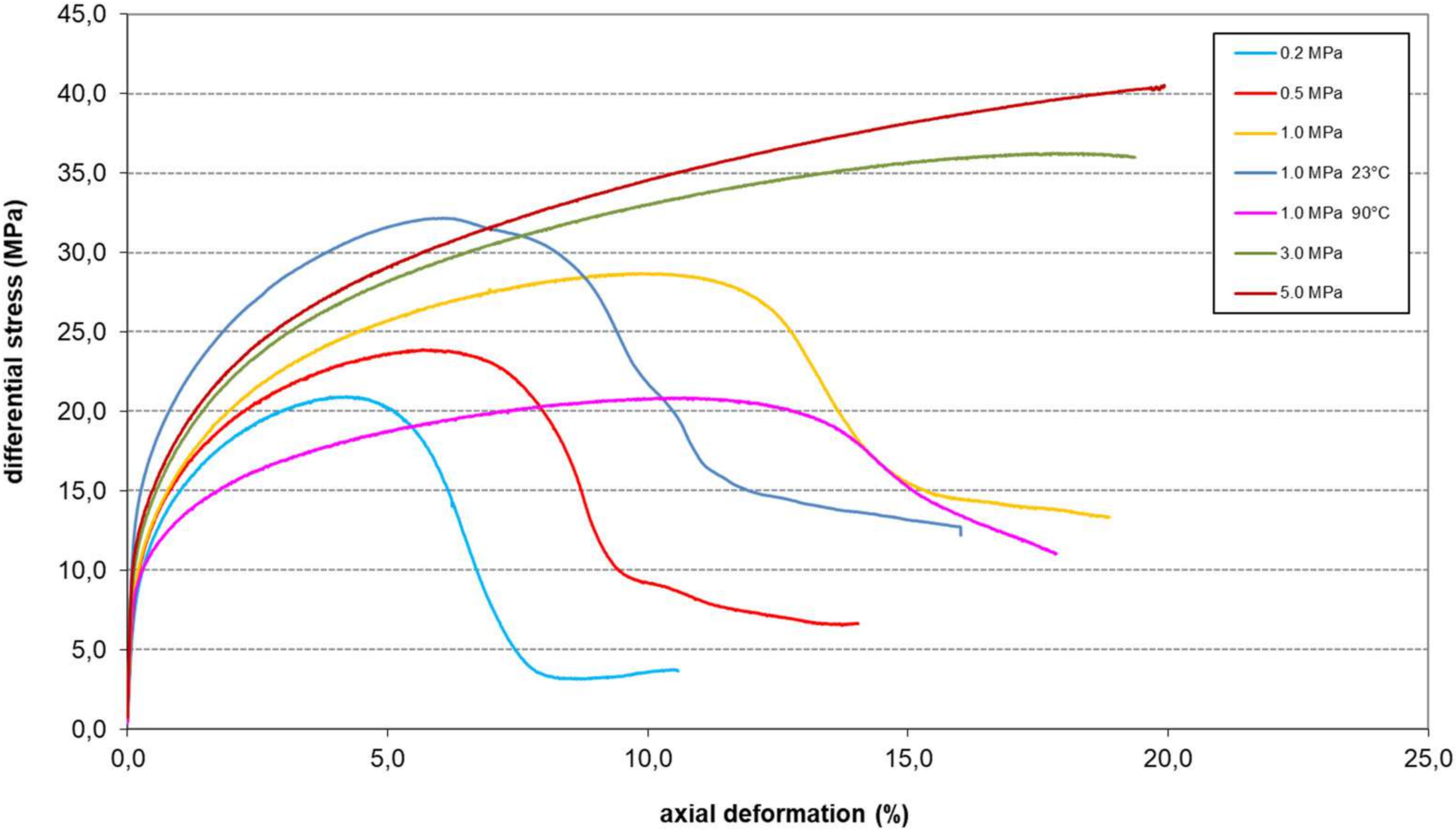
REFLECTED:

AFTER:

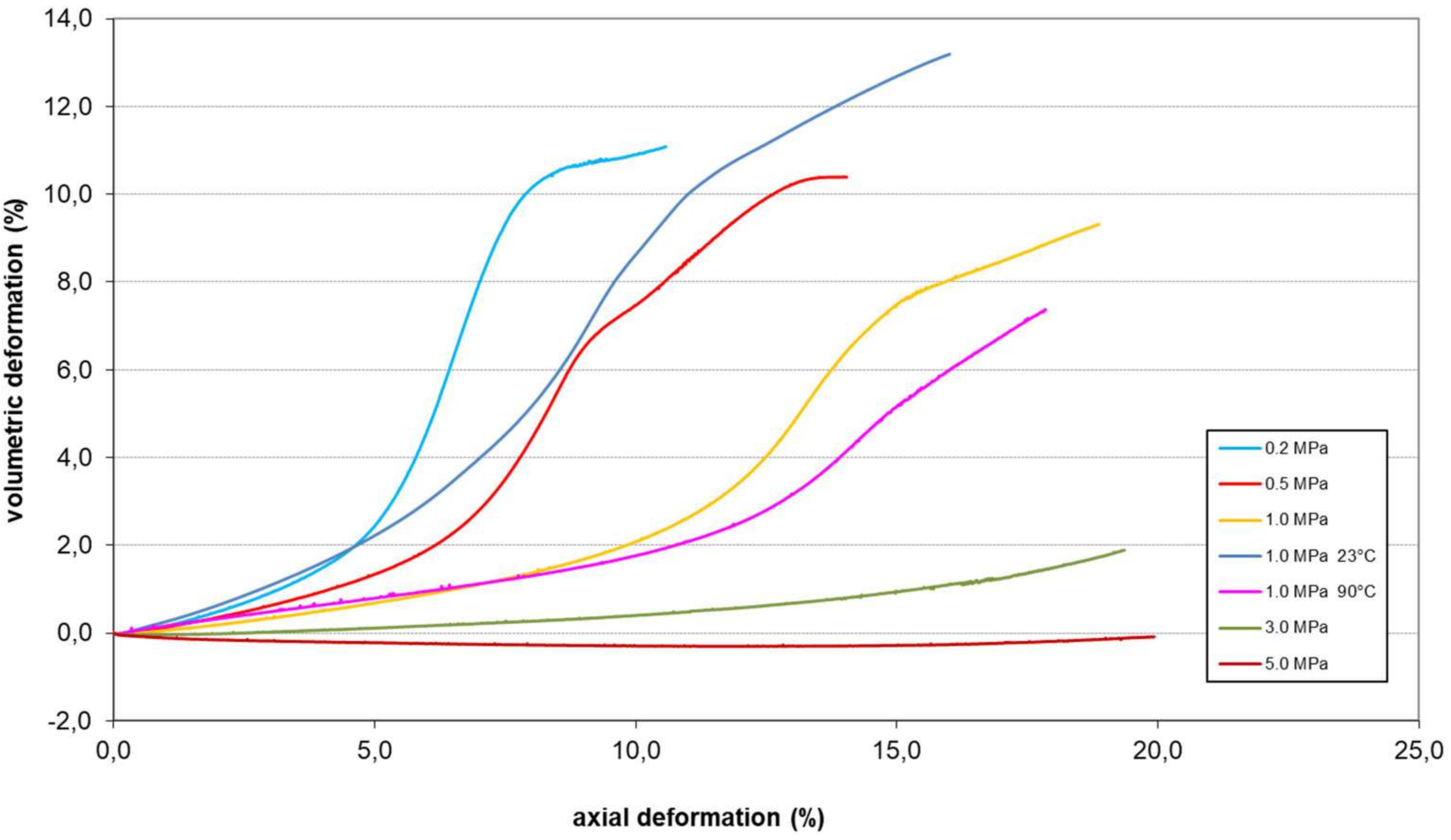
σ_3 = 3.0 MPa T = 57°C	σ_3 = 5.0 MPa T = 57°C	σ_3 = 1.0 MPa T = 90°C



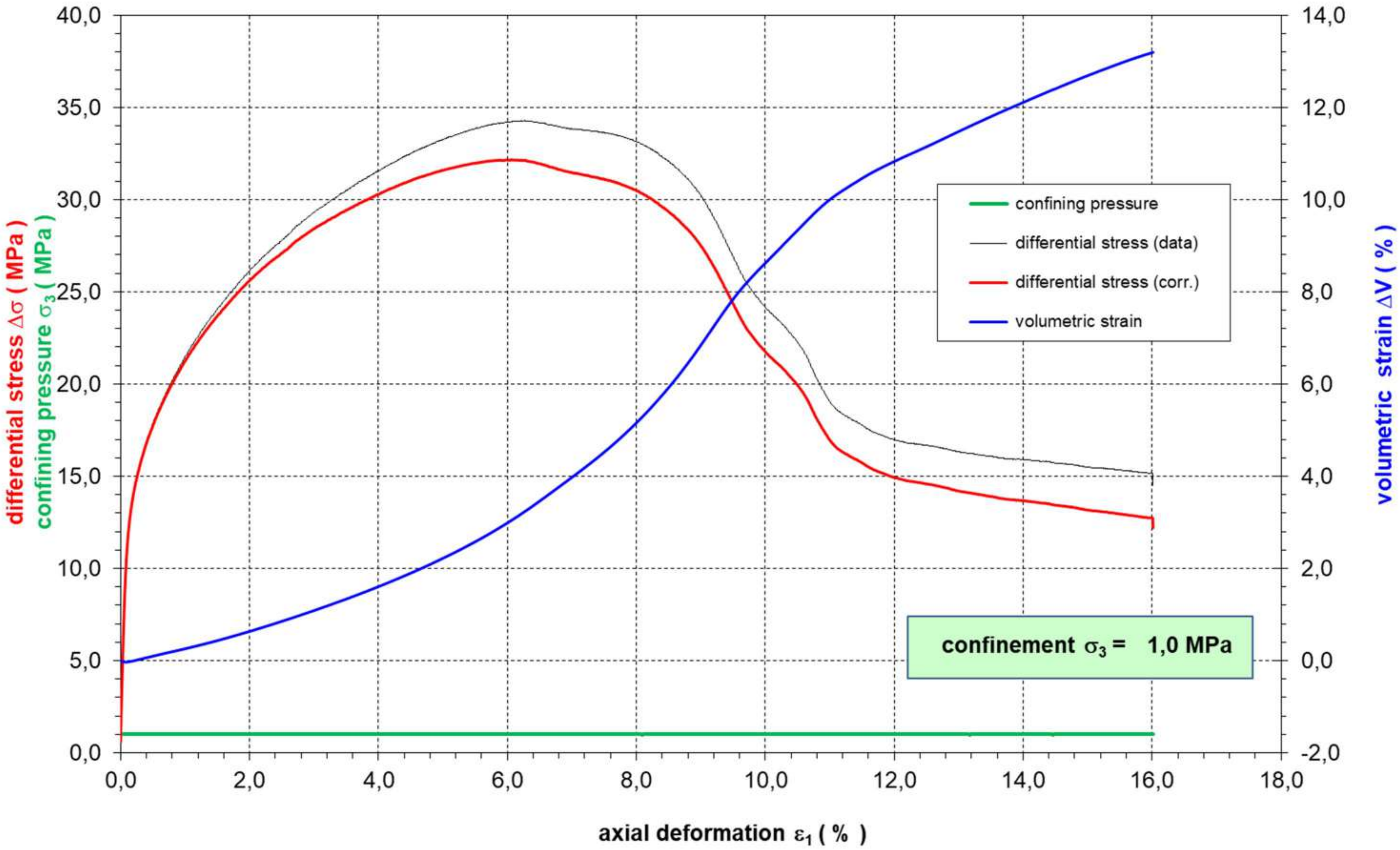
maximum triaxial strength (57°C)
dilatancy strength
23°C
90°C
differential stress σDiff max (MPa)
confining pressure σ3 (MPa)
60,0
50,0
40,0
30,0
20,0
10,0
0,0
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
16,0
18,0
20,0



45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
5,0
0,0
differential stress (MPa)
0,0
5,0
10,0
15,0
20,0
25,0
axial deformation (%)
0.2 MPa
0.5 MPa
1.0 MPa
1.0 MPa 23°C
1.0 MPa 90°C
3.0 MPa
5.0 MPa



14,0
12,0
10,0
8,0
6,0
4,0
2,0
0,0
-2,0
volumetric deformation (%)
0,0
5,0
10,0
15,0
20,0
25,0
axial deformation (%)
0.2 MPa
0.5 MPa
1.0 MPa
1.0 MPa 23°C
1.0 MPa 90°C
3.0 MPa
5.0 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

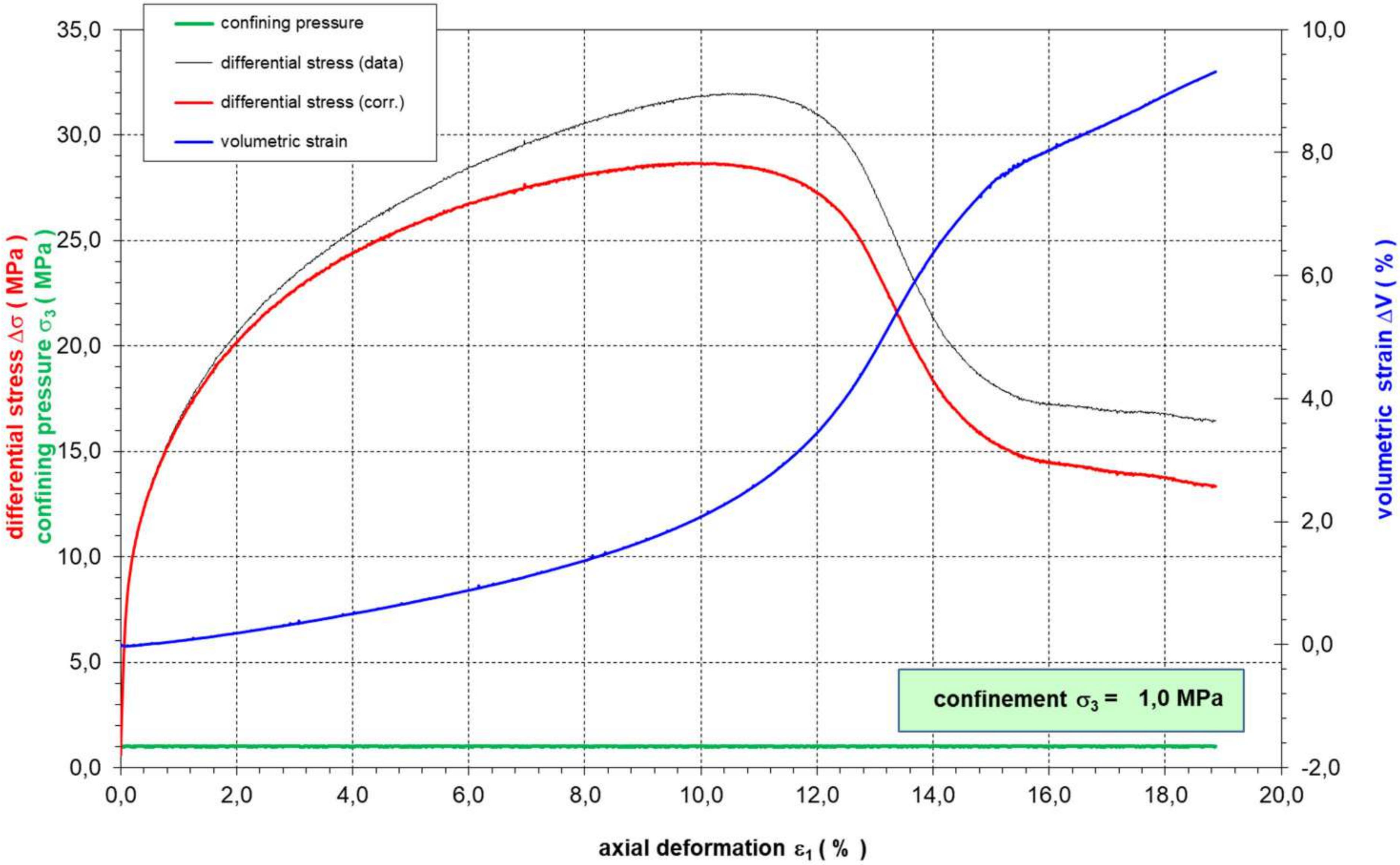
Triaxial strength test (TC_nat)

Unit – PRP (Pure Halite)

→ stress-strain behavior; sample 743/YGM004/TC_d1 @23°C

Appendix 197

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

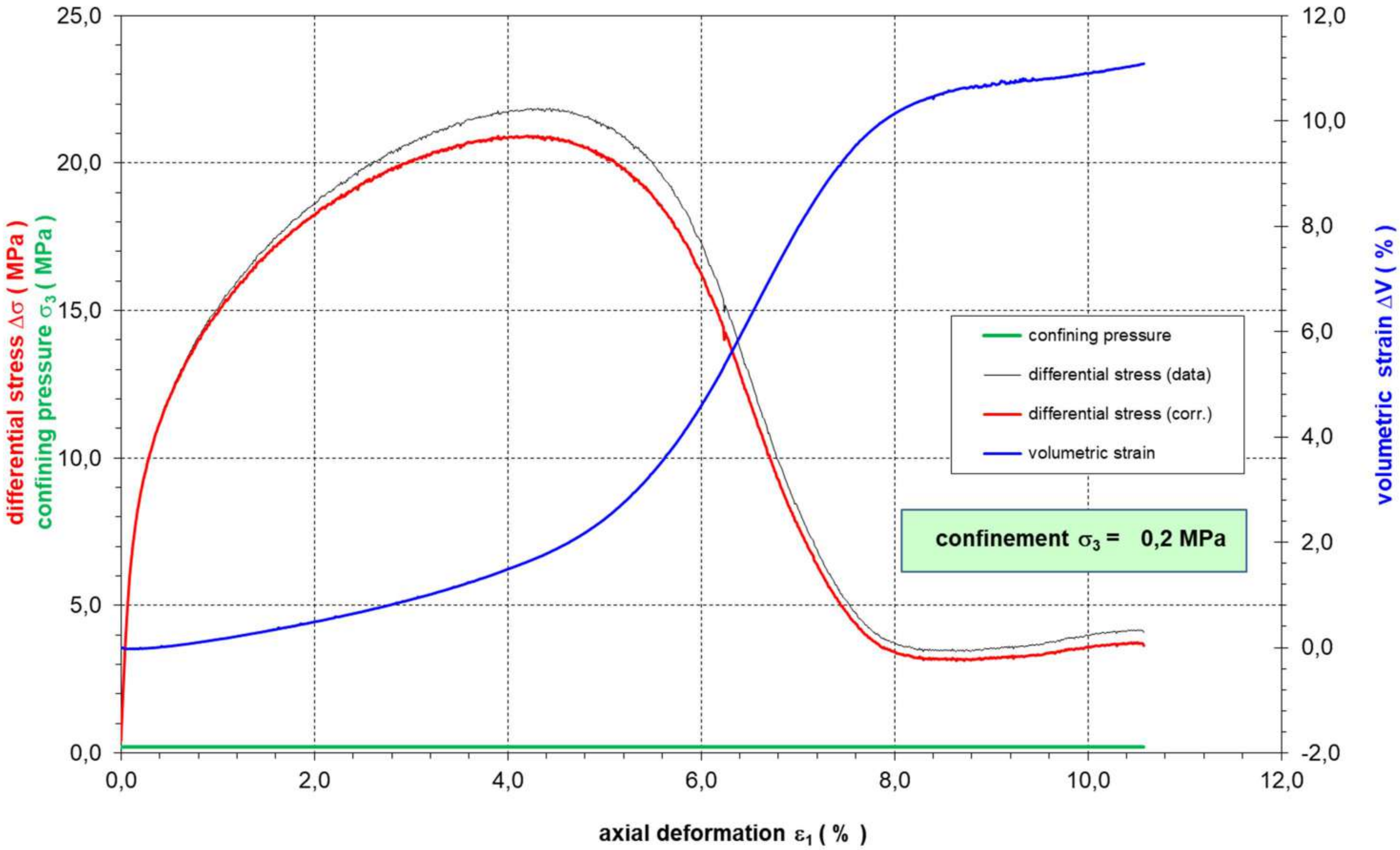
Triaxial strength test (TC_nat)

Unit – PRP (Pure Halite)

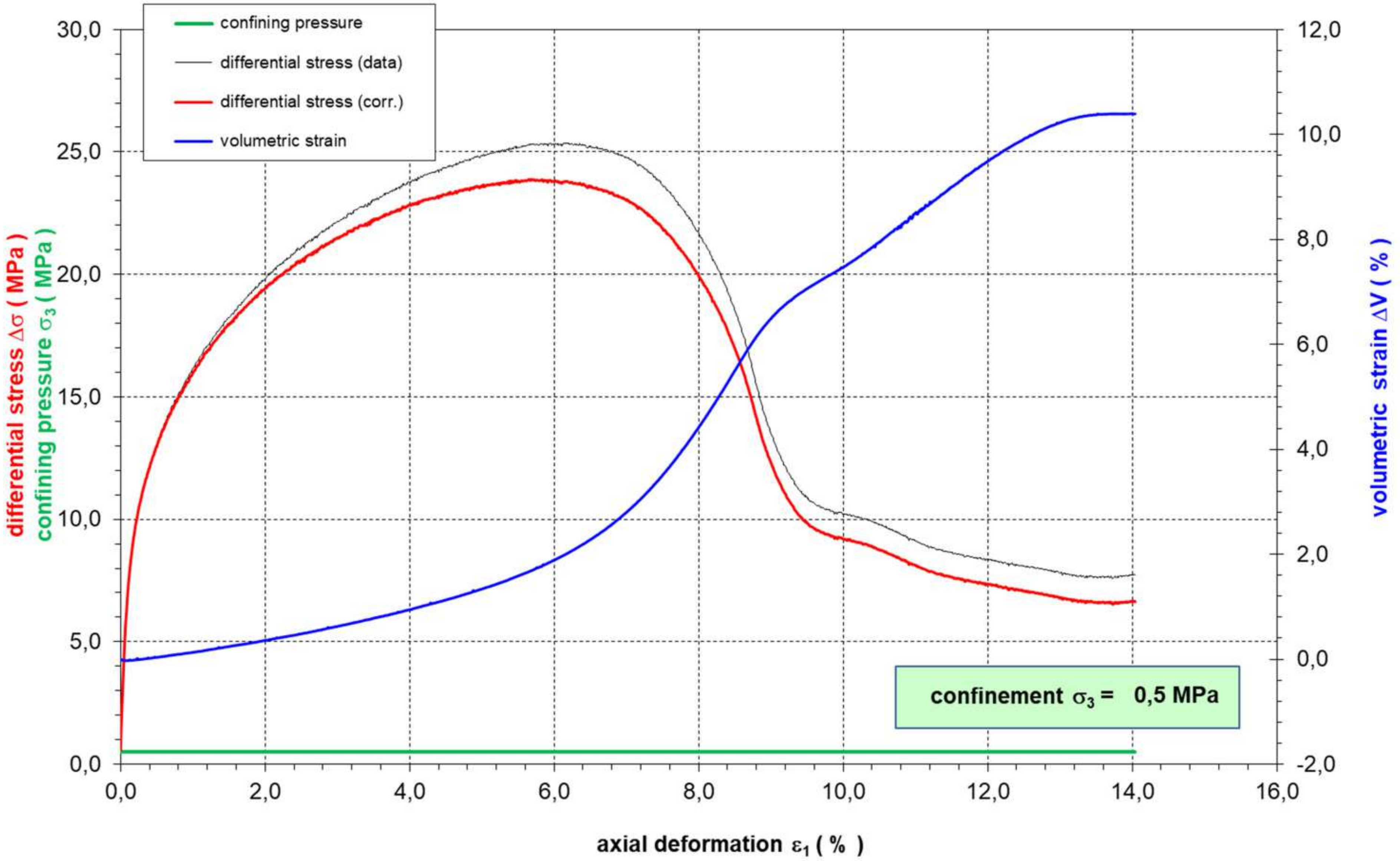
→ stress-strain behavior; sample 743/YGM008/TC_d2 @57°C

Appendix 198

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



differential stress Δσ (MPa)
confining pressure σ_3 (MPa)
volumetric strain ΔV (%)
axial deformation ε_1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ_3 = 0,2 MPa
25,0
20,0
15,0
10,0
5,0
0,0
12,0
10,0
8,0
6,0
4,0
2,0
0,0
-2,0
0,0
2,0
4,0
6,0
8,0
10,0
12,0



INSTITUT FÜR GEBIRGSMECHANIK GMBH

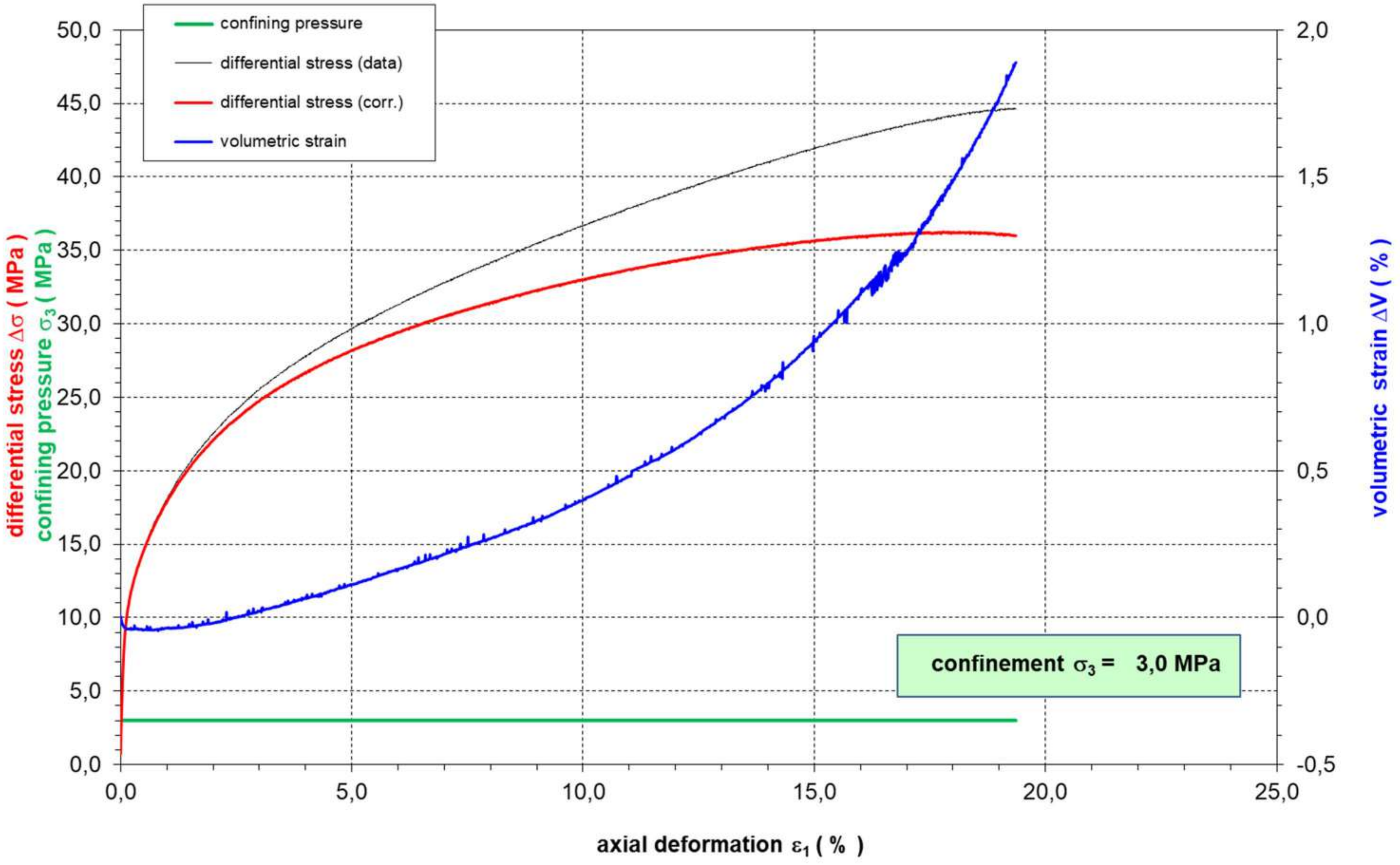
Triaxial strength test (TC_nat)

Unit – PRP (Pure Halite)

→ stress-strain behavior; sample 743/YGM009/TC_d4 @57°C

Appendix 200

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

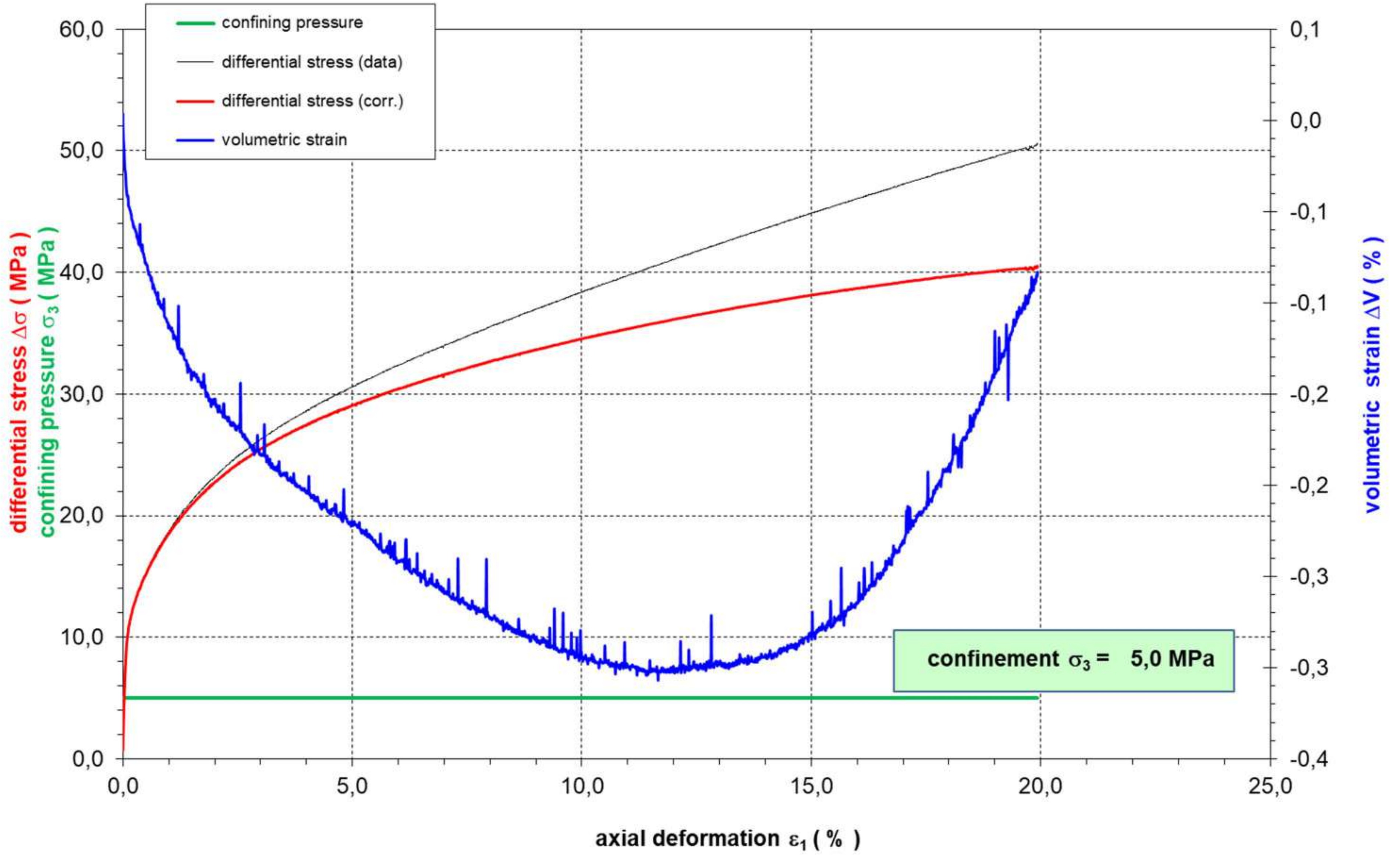
Triaxial strength test (TC_nat)

Unit – PRP (Pure Halite)

→ stress-strain behavior; sample 743/YGM010/TC_d5 @57°C

Appendix 201

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

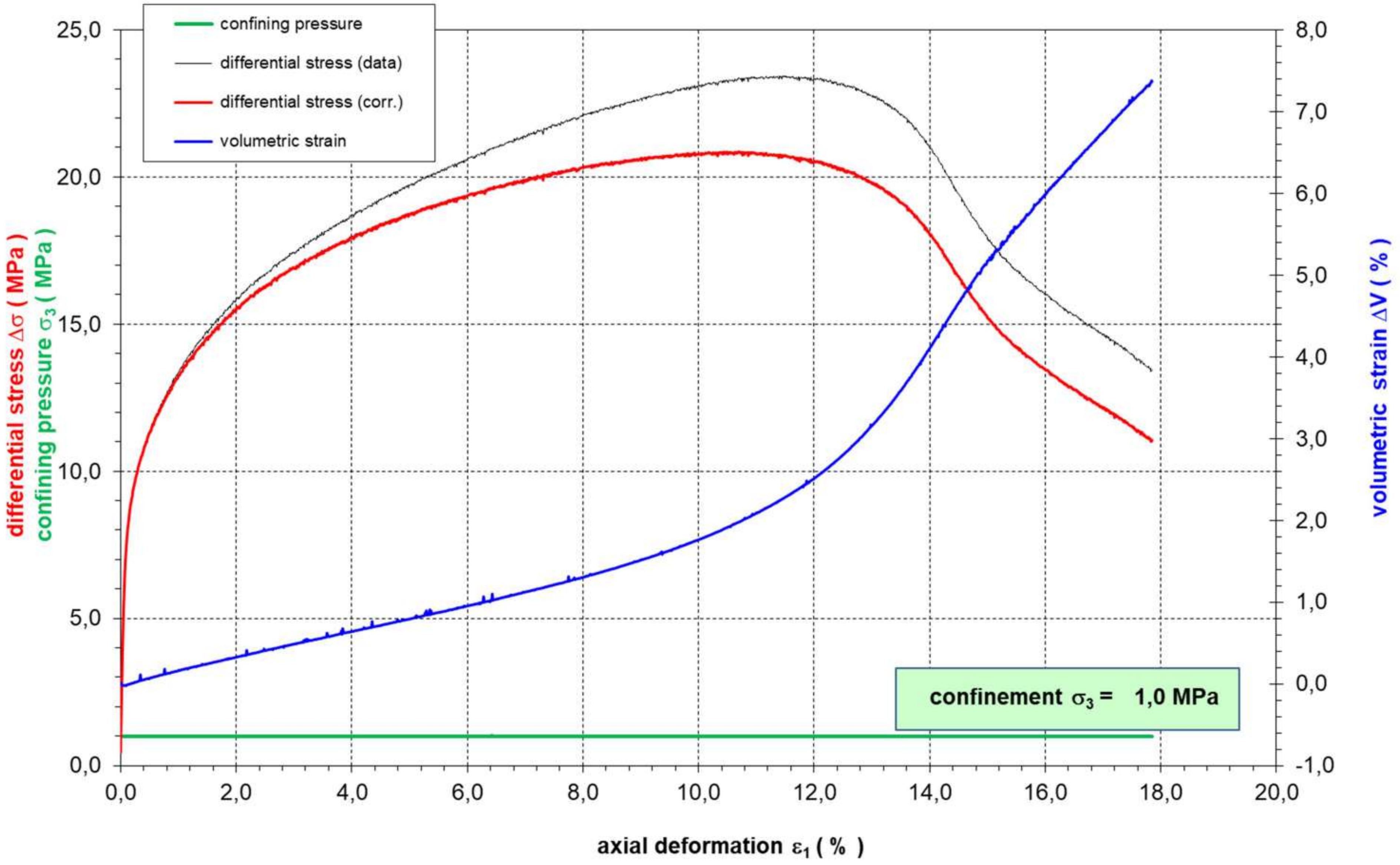
Triaxial strength test (TC_nat)

Unit – PRP (Pure Halite)

→ stress-strain behavior; sample 743/YGM011/TC_d6 @57°C

Appendix 202

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial strength test (TC_nat)

Unit – PRP (Pure Halite)

→ stress-strain behavior; sample 743/YGM012/TC_d7 @90°C

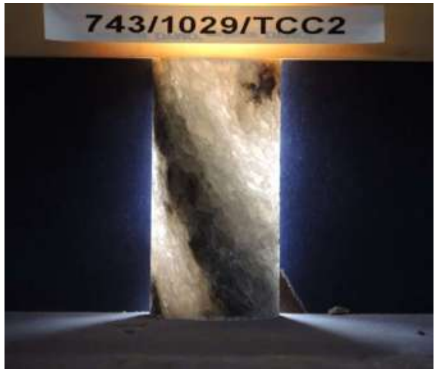
Appendix 203

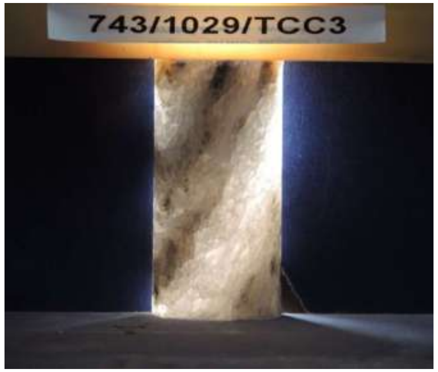
B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

	743/1029/ TCC1	743/1029 /TCC2	743/1029/ TCC3	743/1029/ TCC4	743/1030/ TCC5	743/1030/ TCC6	743/1030/ TCC7	743/1030/ TCC8	743/1102/ TCC9	743/1102/ TCC10	743/1102/ TCC11	743/1102/ TCC12	743/1102/ TCC13
material	pure salt	pure salt	pure salt	pure salt	pure salt	pure salt	pure salt	pure salt	dirty salt	dirty salt – sample broken	dirty salt	dirty salt	dirty salt
length l (mm)	80.51	80.65	80.46	80.61	80.66	80.53	80.33	80.45	80.41	80.52	80.51	80.41	80.31
diameter d (mm)	40.49	40.49	40.57	40.60	40.53	40.49	40.51	40.47	40.37	40.57	40.40	40.46	40.33
mass m (g)	218.90	219.17	220.65	219.79	220.25	219.54	220.03	220.67	220.83	222.09	218.48	221.87	220.1
density ρ (g/cm^3) =	2.112	2.111	2.122	2.106	2.117	2.117	2.125	2.133	2.146	2.133	2.117	2.146	2.146
$V_{p\text{-axial}}$ (km/s) =	-	-	-	-	-	-	-	-	3.989	3.888	-	3.939	4.01
$V_{p\text{-radial: a-c}}$ (km/s) =	3.492	3.584	3.914	2.844	3.617	3.595	2.049	3.349	4.421	4.037	4.191	4.556	4.46
$V_{p\text{-radial: b-d}}$ (km/s) =	-	-	-	-	3.538	-	4.033	1.794	4.086	4.025	3.953	4.500	4.16
$V_{s\text{-axial}}$ (km/s) =	-	-	-	-	-	-	-	-	2.495	2.422	-	2.451	2.39
E_d =	-	-	-	-	-	-	-	-	31.49	29.60	-	30.53	30.53
K_d =	-	-	-	-	-	-	-	-	16.33	15.57	-	16.12	16.12
G_d =	-	-	-	-	-	-	-	-	13.36	12.51	-	12.89	12.89
ν_d =	-	-	-	-	-	-	-	-	0.18	0.18	-	0.18	0.18

reflected light:

transmitted light:





TCC1	TCC2	TCC3	TCC4
σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa
σ_{diff} = 12.0 / 10.0 MPa	σ_{diff} = 12.0 / 10.0 MPa	σ_{diff} = 16.0 / 14.0 MPa	σ_{diff} = 19.0 / 16.0 MPa

Samples for triaxial creep tests (TCC)

Unit – PRP (Pure Halite)

→ photo-documentation before the test

BEFORE:

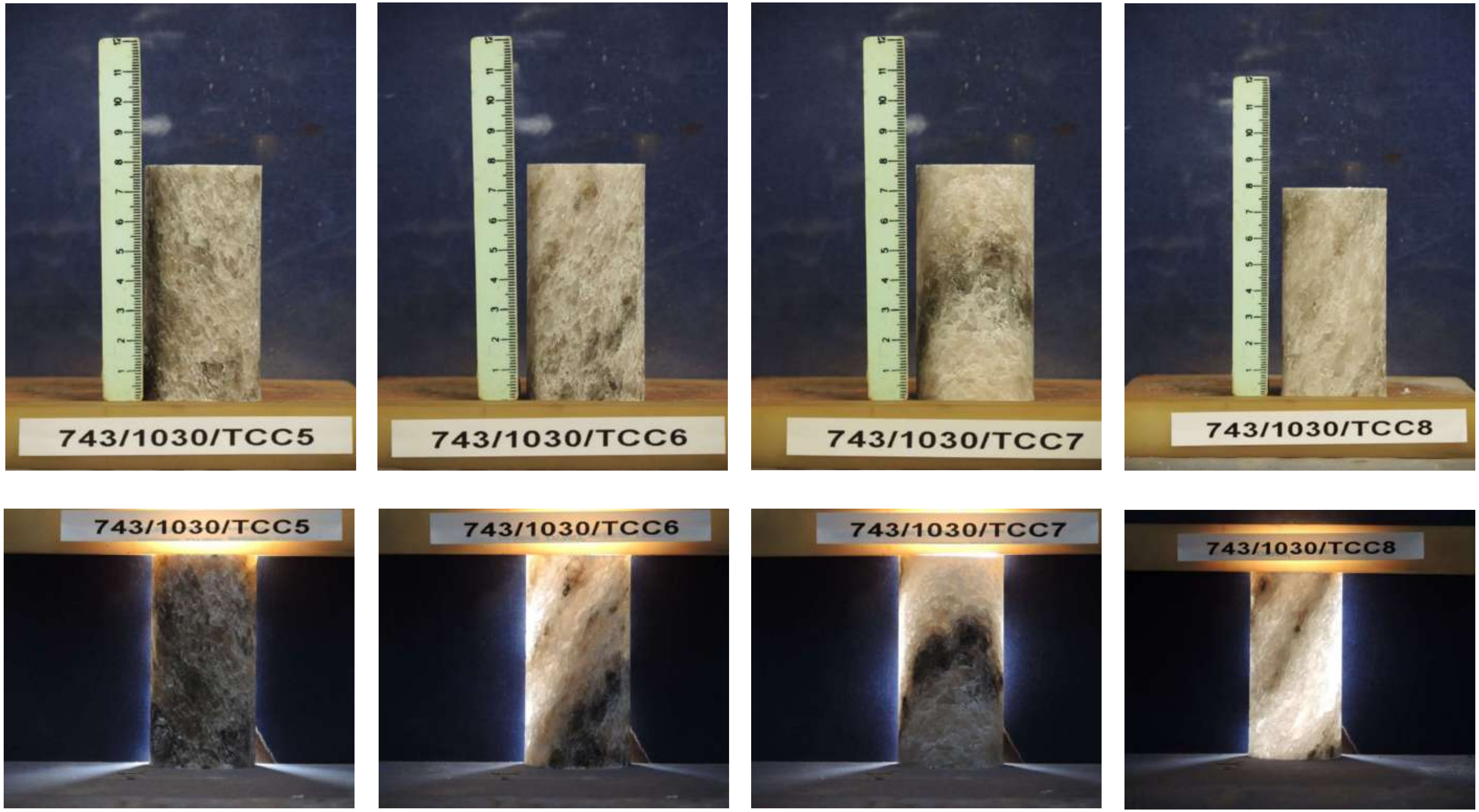
AFTER:

Tests still running

σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa
σ_{diff} = 12.0 / 10.0 MPa	σ_{diff} = 12.0 / 10.0 MPa	σ_{diff} = 16.0 / 14.0 MPa	σ_{diff} = 19.0 / 16.0 MPa

reflected light:

transmitted light:



TCC5	TCC6	TCC7	TCC8
σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa
σ_{diff} = 22.0 / 19.0 MPa	σ_{diff} = 25.0 / 22.0 MPa	σ_{diff} = 16.0 / 14.0 MPa	σ_{diff} = 16.0 / 14.0 MPa

BEFORE:

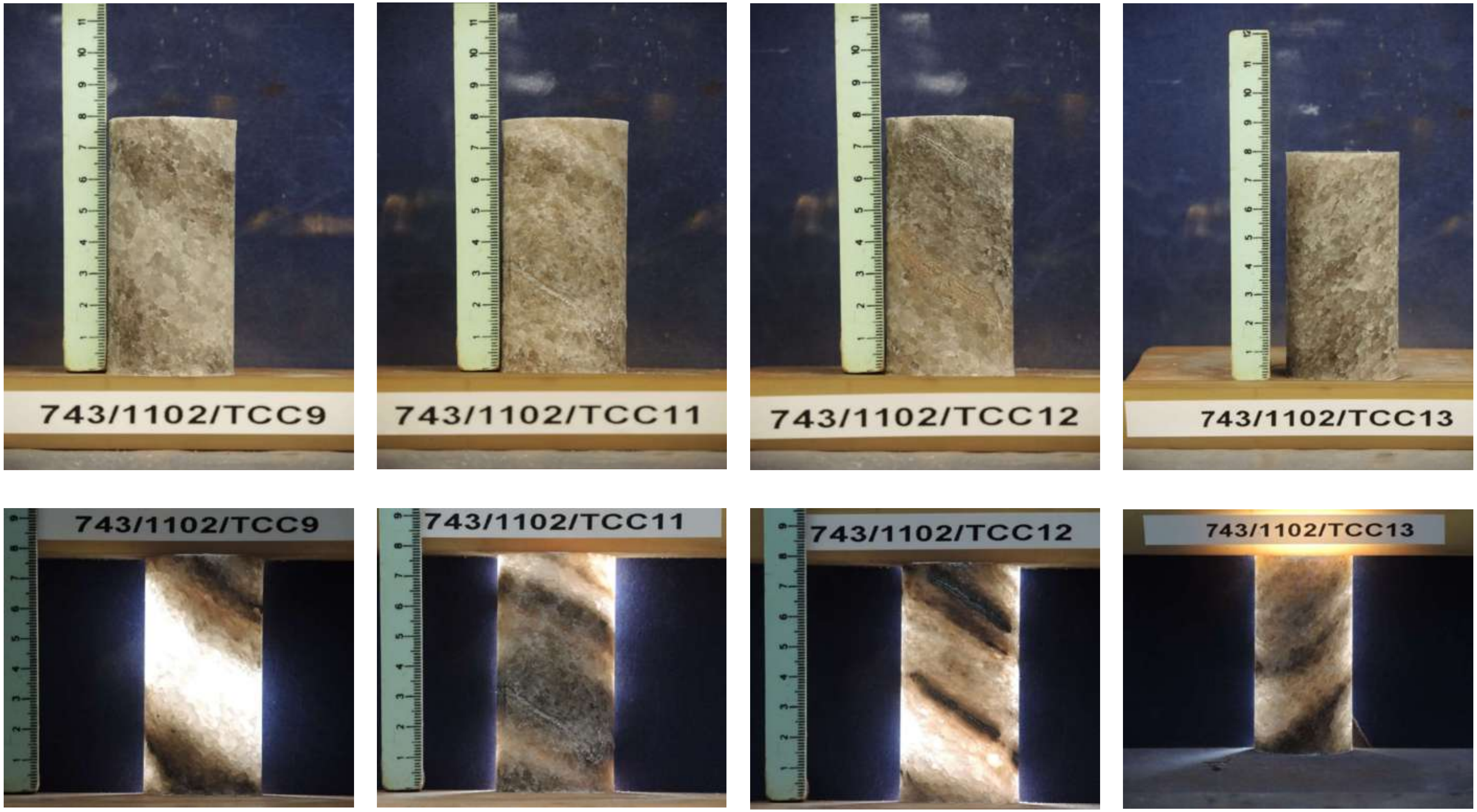
AFTER:

Tests still running

σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa	σ_3 = 20.0 MPa
σ_{diff} = 22.0 / 19.0 MPa	σ_{diff} = 25.0 / 22.0 MPa	σ_{diff} = 16.0 / 14.0 MPa	σ_{diff} = 16.0 / 14.0 MPa

reflected light:

transmitted light:



σ_3 = 20.0 MPa
σ_{diff} = 16.0 / 14.0 MPa

σ_3 = 20.0 MPa
σ_{diff} = 18.0 / 16.0 MPa

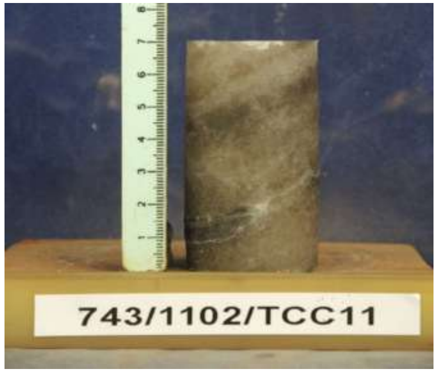
σ_3 = 20.0 MPa
σ_{diff} = 24.0 / 22.0 MPa

σ_3 = 20.0 MPa
σ_{diff} = 8.0 / 10.0 MPa

BEFORE:

AFTER:

Test still running



Test still running

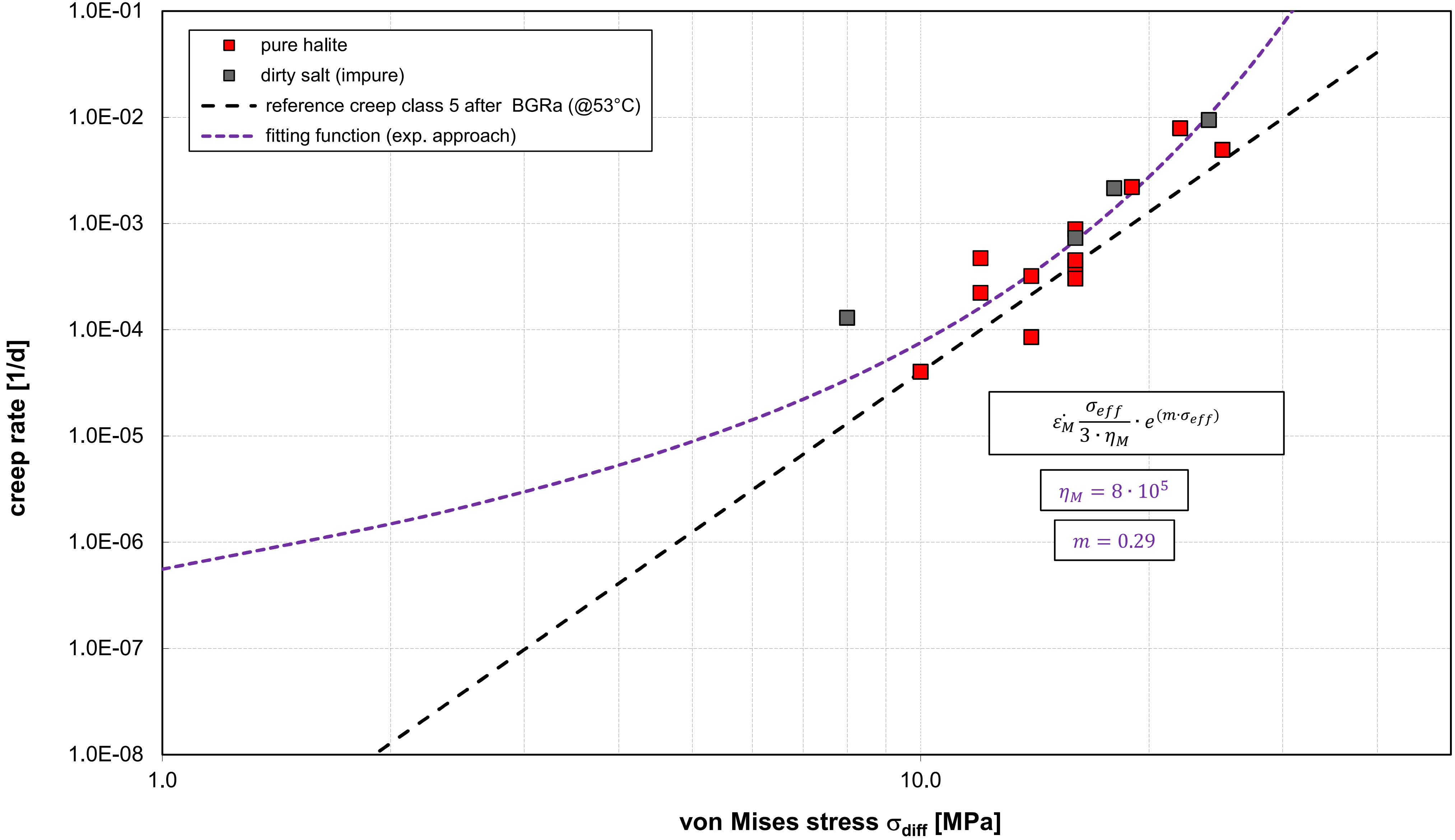
σ_3 = 20.0 MPa
σ_{diff} = 16.0 / 14.0 MPa

σ_3 = 20.0 MPa
σ_{diff} = 18.0 / 16.0 MPa

σ_3 = 20.0 MPa
σ_{diff} = 24.0 / 22.0 MPa

σ_3 = 20.0 MPa
σ_{diff} = 8.0 / 10.0 MPa

sample	material	comment	axial stress σ_1 (MPa)	confining pressure σ_3 (MPa)	differential stress $\Delta\sigma$ (MPa)	temperature (°C)	creep rate (1/d)
743/cx1029/TCC1	**pure halite**	**ready**	32	20	12	53	2.22E-04
743/cx1029/TCC1	**pure halite**	**running**	30	20	10	53	2.05E-05
743/cx1029/TCC2	**pure halite**	**running**	32	20	12	53	5.58E-04
743/cx1029/TCC2	**pure halite**	**not startet yet**	30	20	10	53	
743/cx1029/TCC3	**pure halite**	**ready**	36	20	16	53	8.79E-04
743/cx1029/TCC3	**pure halite**	**running**	34	20	14	53	2.67E-04
743/cx1029/TCC4	**pure halite**	**ready**	39	20	19	53	2.20E-03
743/cx1029/TCC4	**pure halite**	**running**	36	20	16	53	3.70E-04
743/cx1030/TCC5	**pure halite**	**finished**	42	20	22	53	7.87E-03
743/cx1030/TCC5	**pure halite**	**not possible**	39	20	19	53	
743/cx1030/TCC6	**pure halite**	**finished**	45	20	25	53	4.93E-03
743/cx1030/TCC6	**pure halite**	**not possible**	30	20	10	53	
743/cx1030/TCC7	**pure halite**	**ready**	36	20	16	23	3.02E-04
743/cx1030/TCC7	**pure halite**	**running**	34	20	14	23	8.08E-05
743/cx1030/TCC8	**pure halite**	**running**	36	20	16	80	5.55E-04
743/cx1030/TCC8	**pure halite**	**not startet yet**	34	20	14	80	
743/cx1102/TCC9	**dirty salt; impure**	**running**	36	20	16	53	8.15E-04
743/cx1102/TCC9	**dirty salt; impure**	**not startet yet**	34	20	14	53	
743/cx1102/TCC11	**dirty salt; impure**	**finished**	38	20	18	53	2.15E-03
743/cx1102/TCC11	**dirty salt; impure**	**not possible**	36	20	16	53	
743/cx1102/TCC12	**dirty salt; impure**	**finished**	44	20	24	53	9.41E-03
743/cx1102/TCC12	**dirty salt; impure**	**not possible**	42	20	22	53	
743/cx1102/TCC13	**dirty salt; impure**	**running**	28	20	8	53	1.49E-04
743/cx1102/TCC13	**dirty salt; impure**	**not startet yet**	30	20	10	53	



INSTITUT FÜR GEBIRGSMECHANIK GMBH

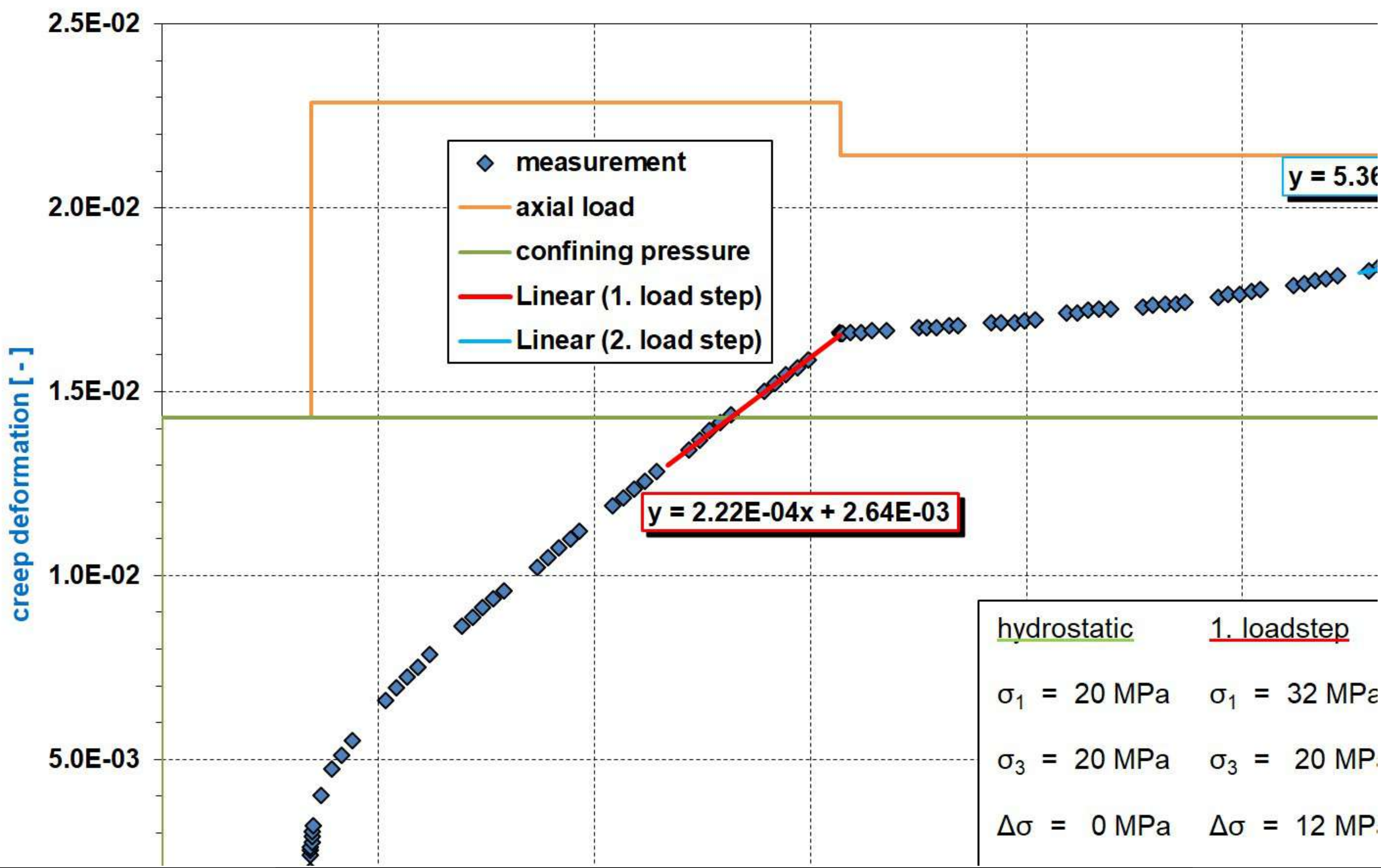
Triaxial creep tests (TCC)

Unit – PRP (Pure Halite & Impure Halite)

→ stationary creep rates v von Mises stress

Appendix 212

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

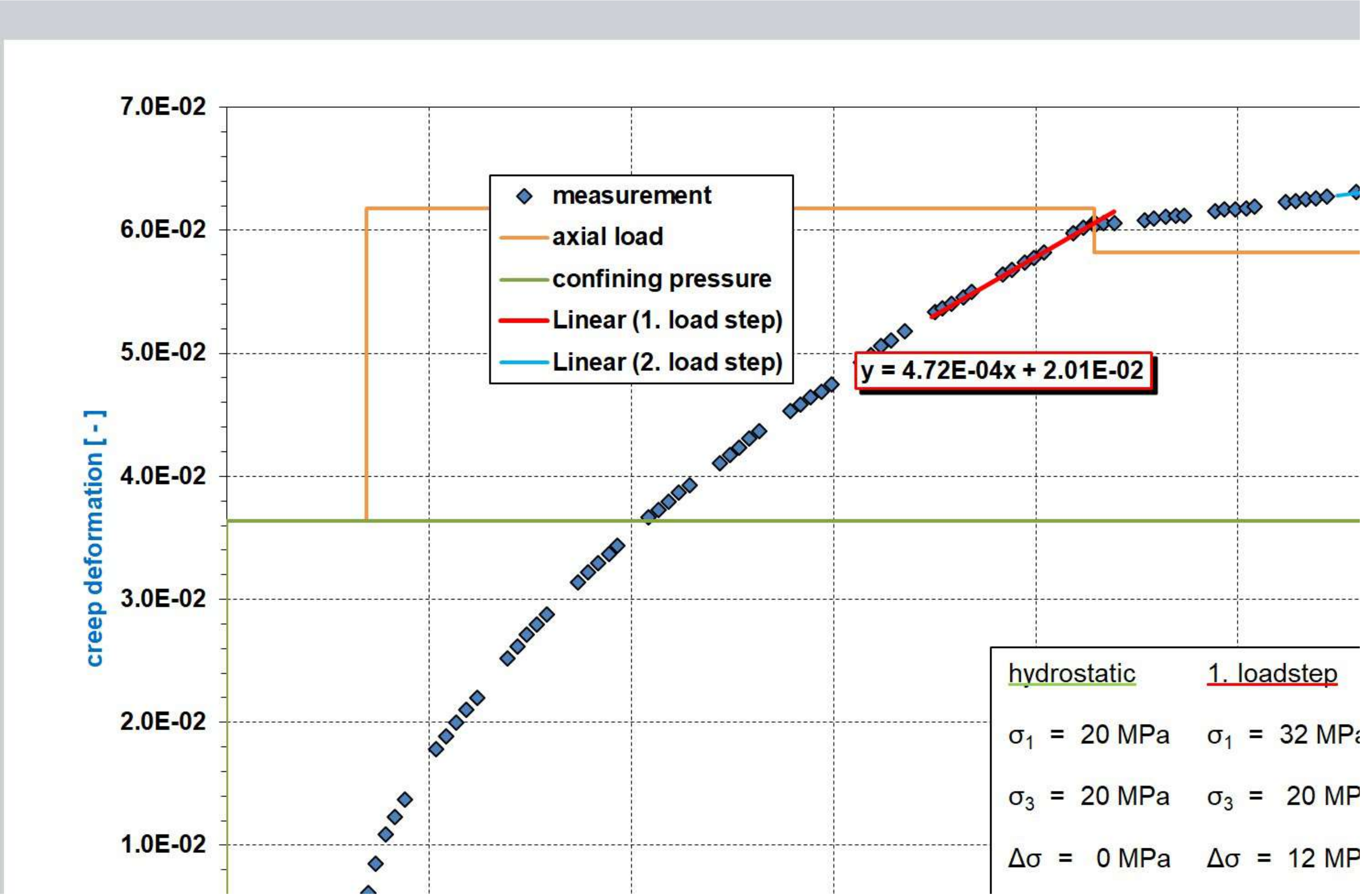
Triaxial creep test (TCC)

Unit – PRP (Pure Halite)

743/cx1029/TCC1

Appendix 213

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

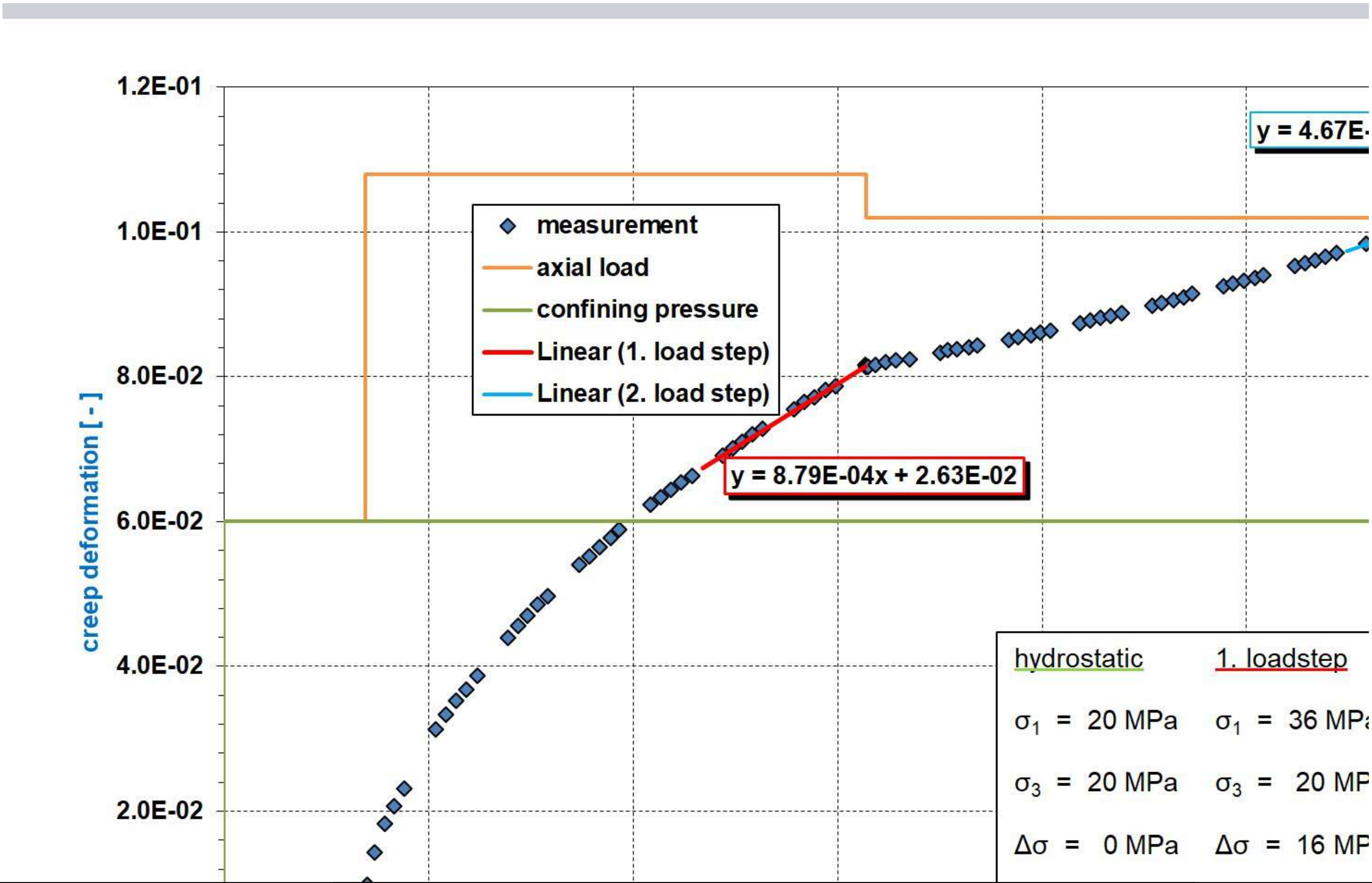
Triaxial creep test (TCC)

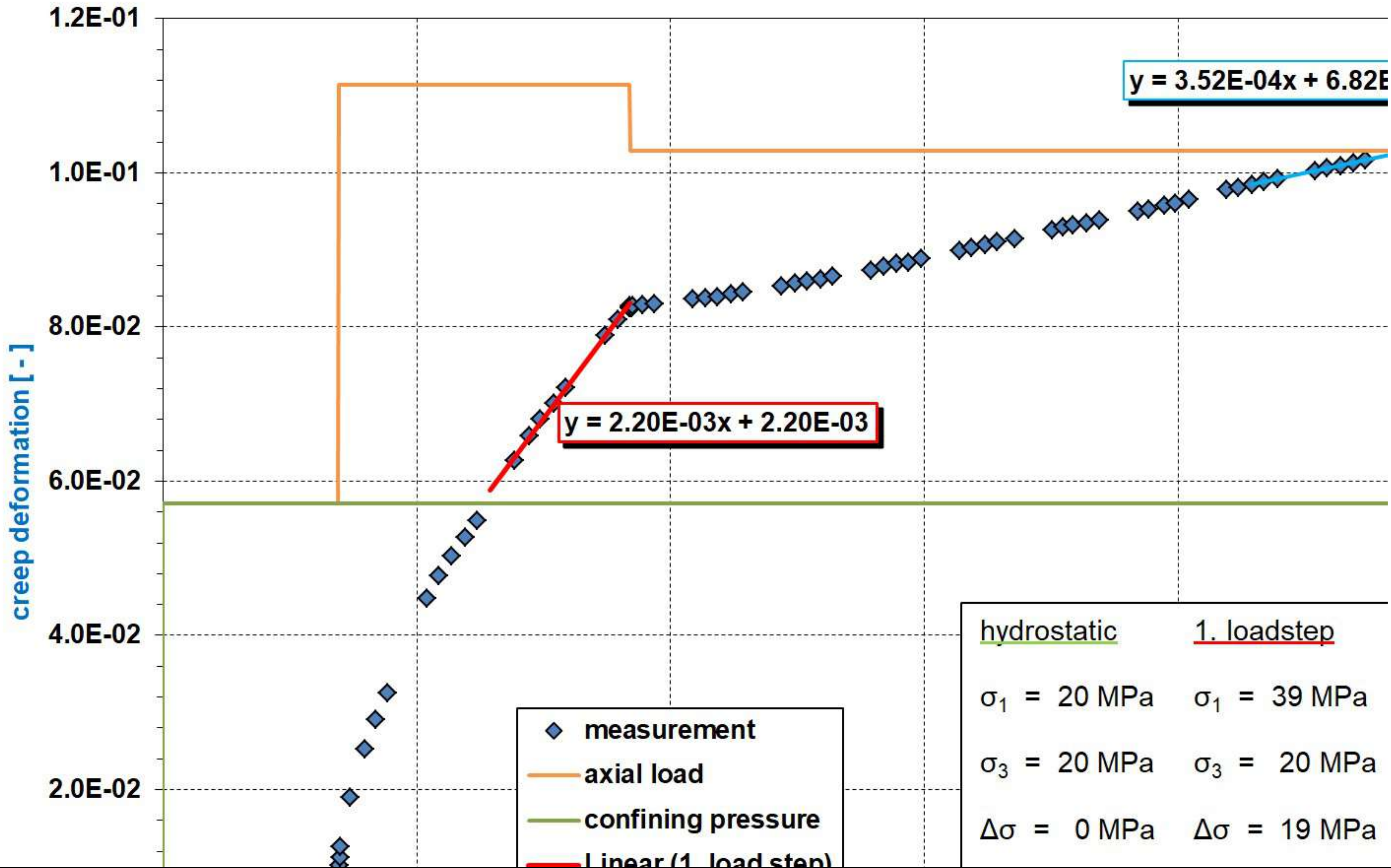
Unit – PRP (Pure Halite)

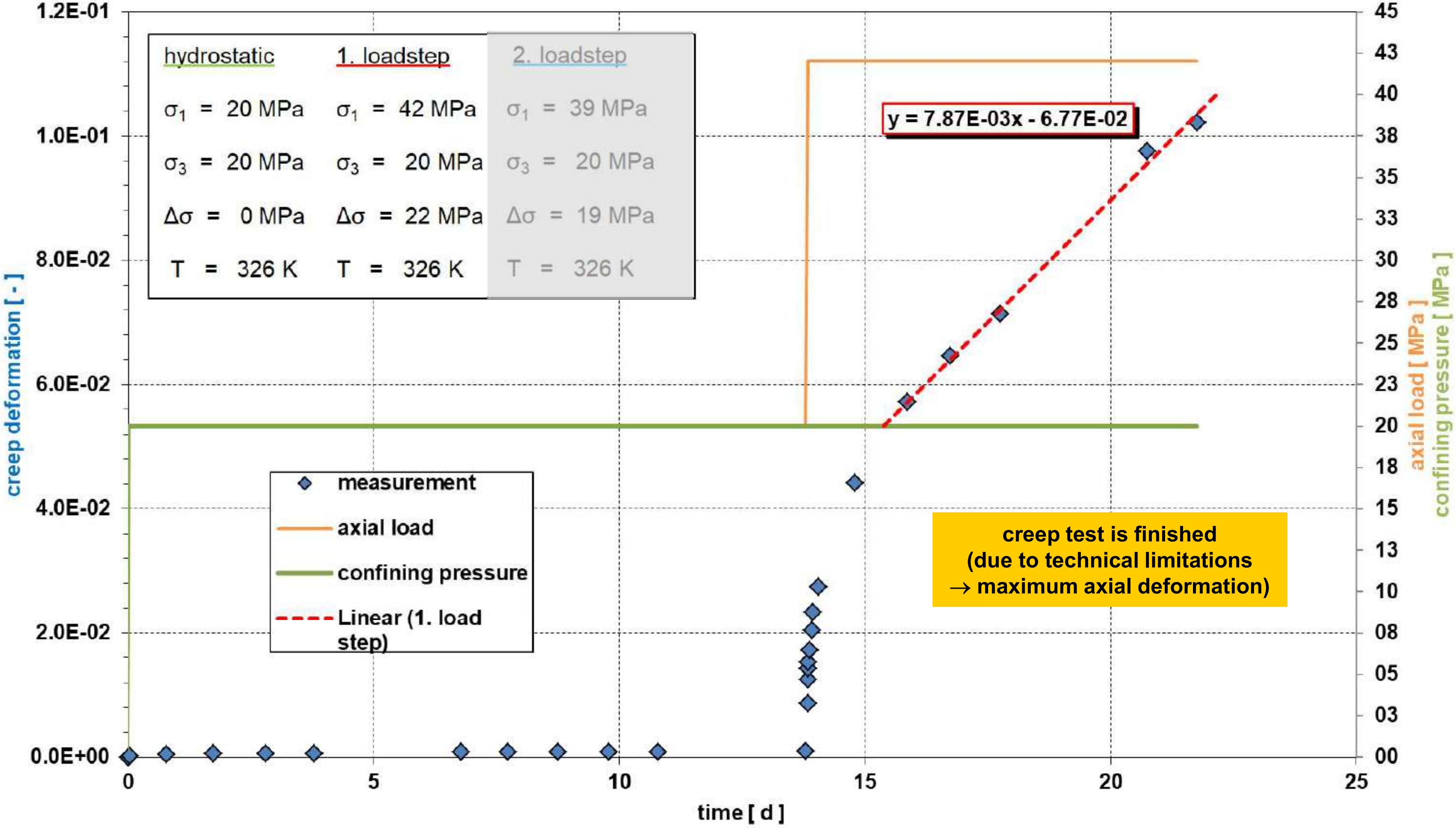
743/cx1029/TCC2

Appendix 214

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"


1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
creep deformation [-]
y = 4.67E-
measurement
axial load
confining pressure
Linear (1. load step)
Linear (2. load step)
y = 8.79E-04x + 2.63E-02
hydrostatic
1. loadstep
σ1 = 20 MPa
σ1 = 36 MP
σ3 = 20 MPa
σ3 = 20 MP
Δσ = 0 MPa
Δσ = 16 MP


1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
creep deformation [-]
y = 3.52E-04x + 6.82E
y = 2.20E-03x + 2.20E-03
measurement
axial load
confining pressure
Linear (1. load step)
hydrostatic
1. loadstep
σ1 = 20 MPa
σ1 = 39 MPa
σ3 = 20 MPa
σ3 = 20 MPa
Δσ = 0 MPa
Δσ = 19 MPa



project: 22/2021 Braskem - sample: 743/1030/TCC5 rock salt

INSTITUT FÜR GEBIRGSMECHANIK GMBH

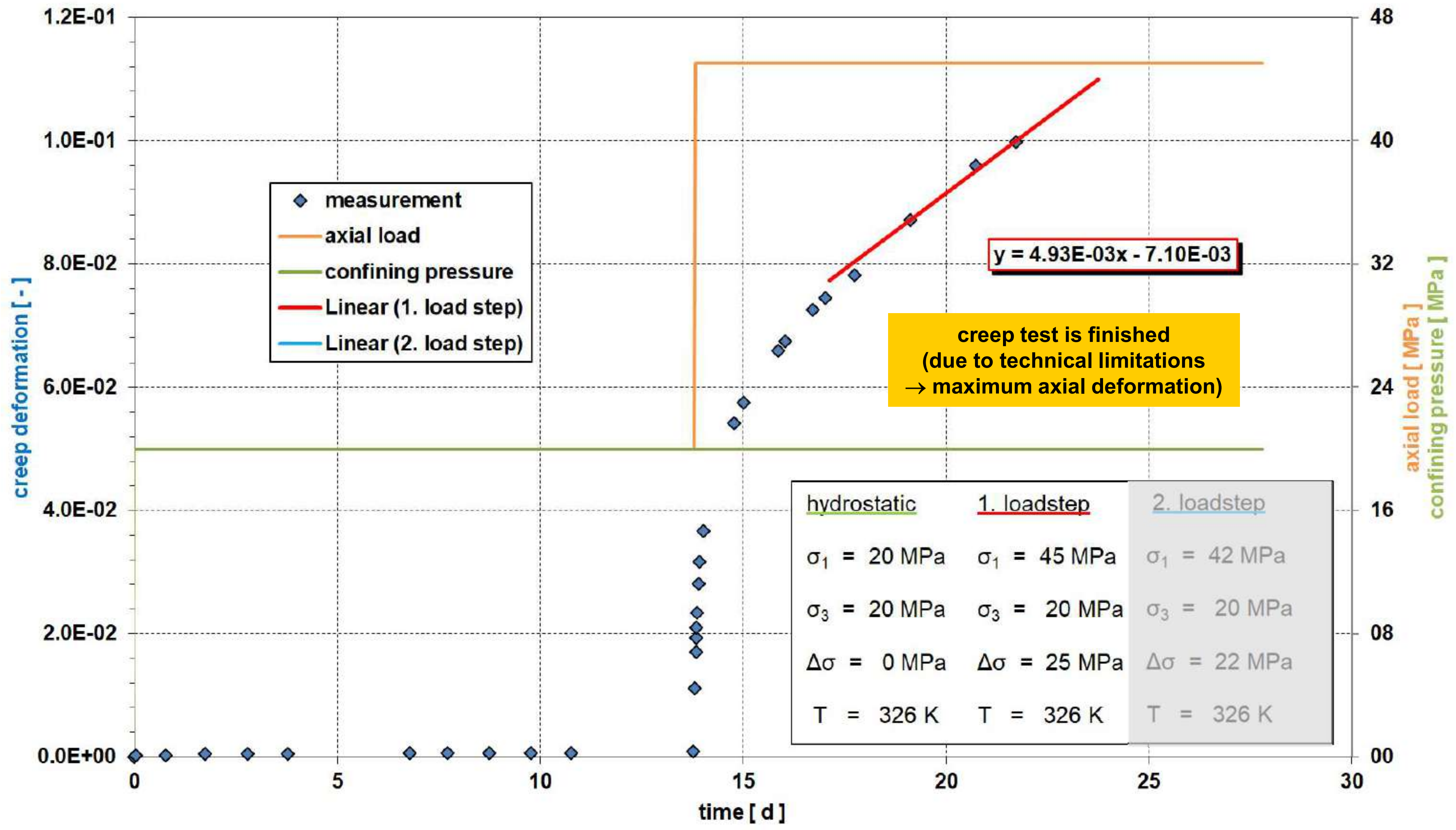
Triaxial creep test (TCC)

Unit – PRP (Pure Halite)

743/cx1030/TCC5

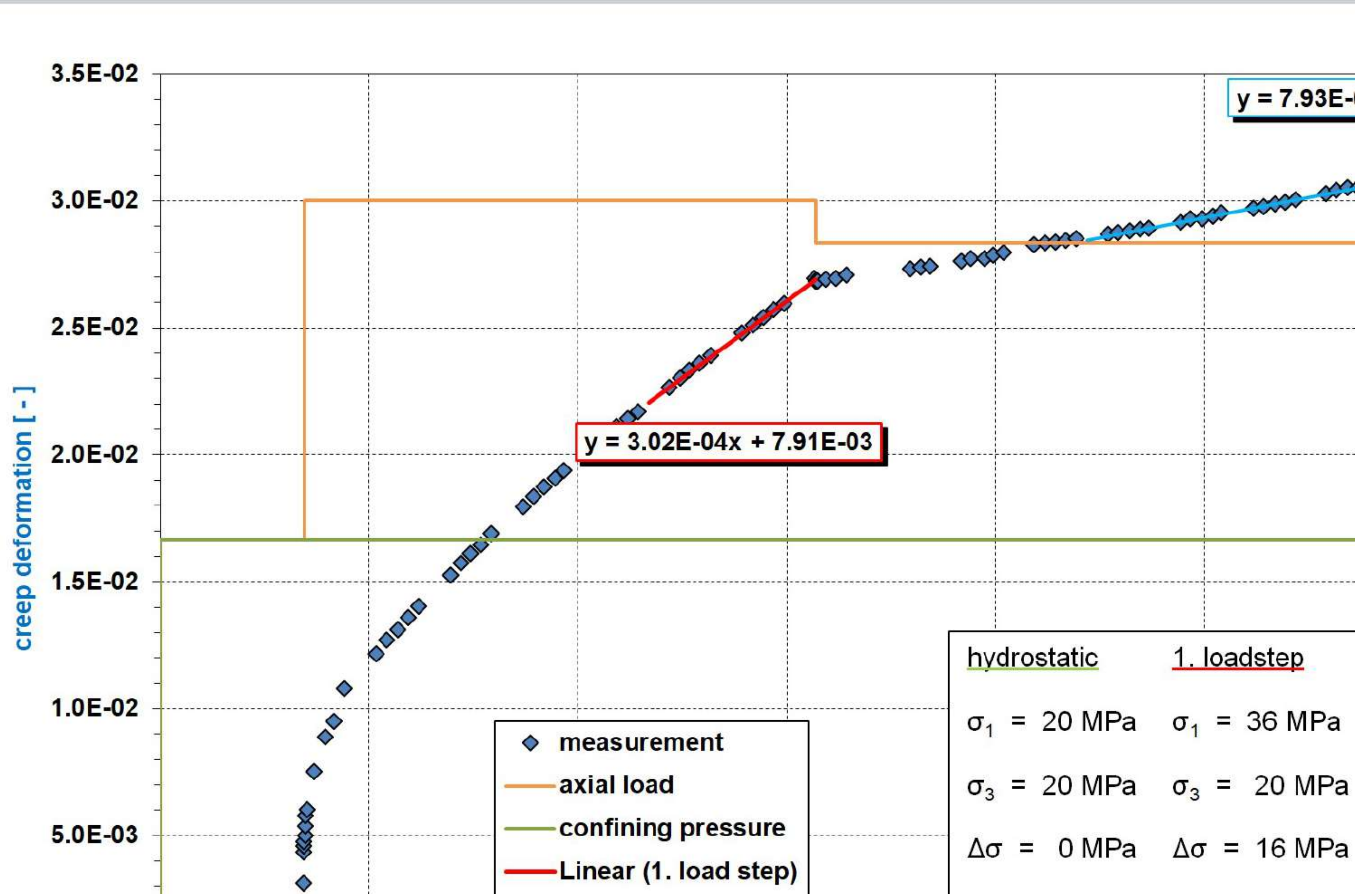
Appendix 217

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



project: 22/2021 Braskem - sample: 743/1030/TCC6 rock salt

INSTITUT FÜR GEBIRGSMECHANIK GMBH	Triaxial creep test (TCC) **Unit – PRP (Pure Halite)** 743/cx1030/TCC6	**Appendix 218** *B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"*

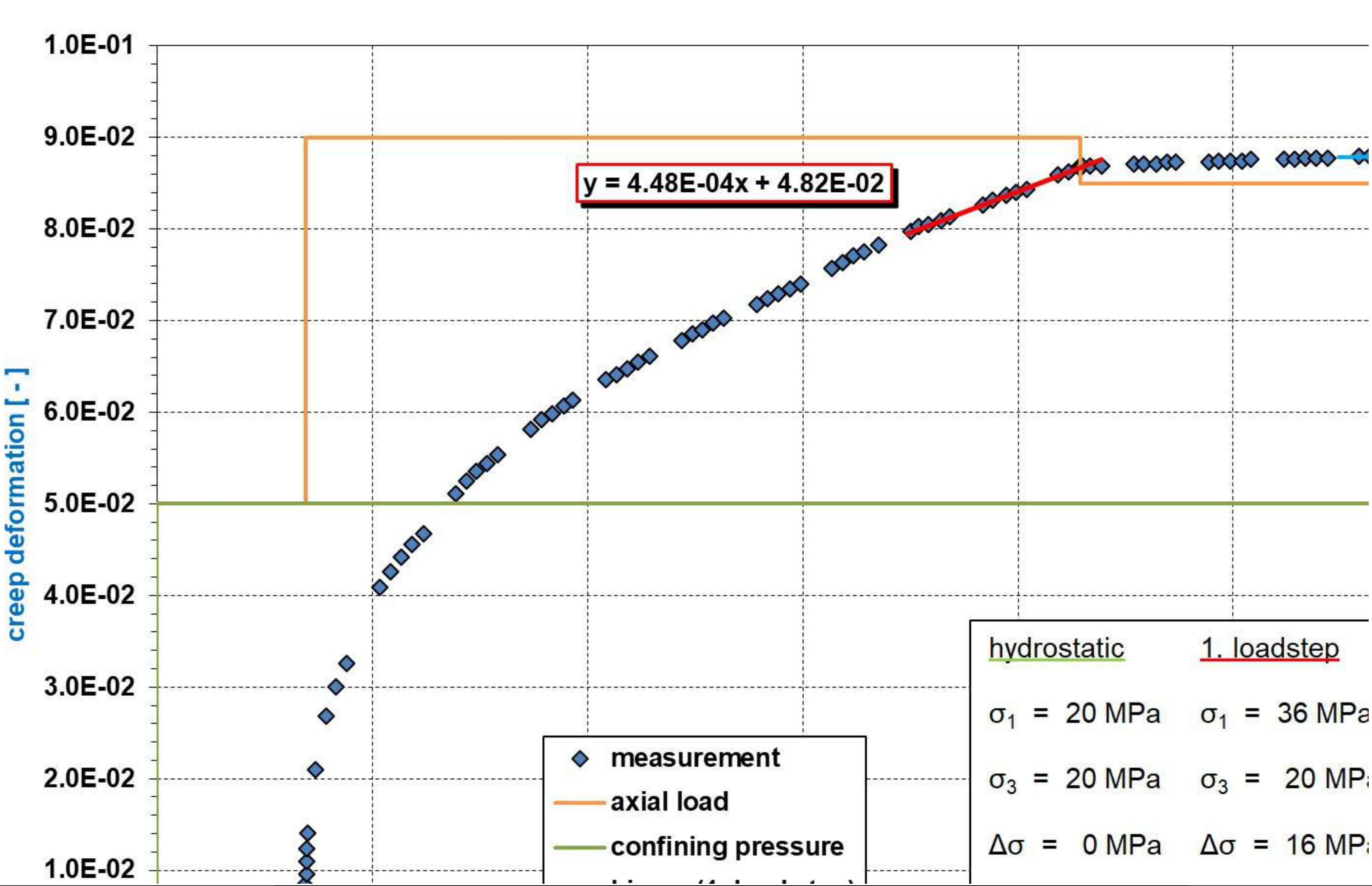


INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial creep test (TCC)

Unit – PRP (Pure Halite)

743/cx1030/TCC7



INSTITUT FÜR GEBIRGSMECHANIK GMBH

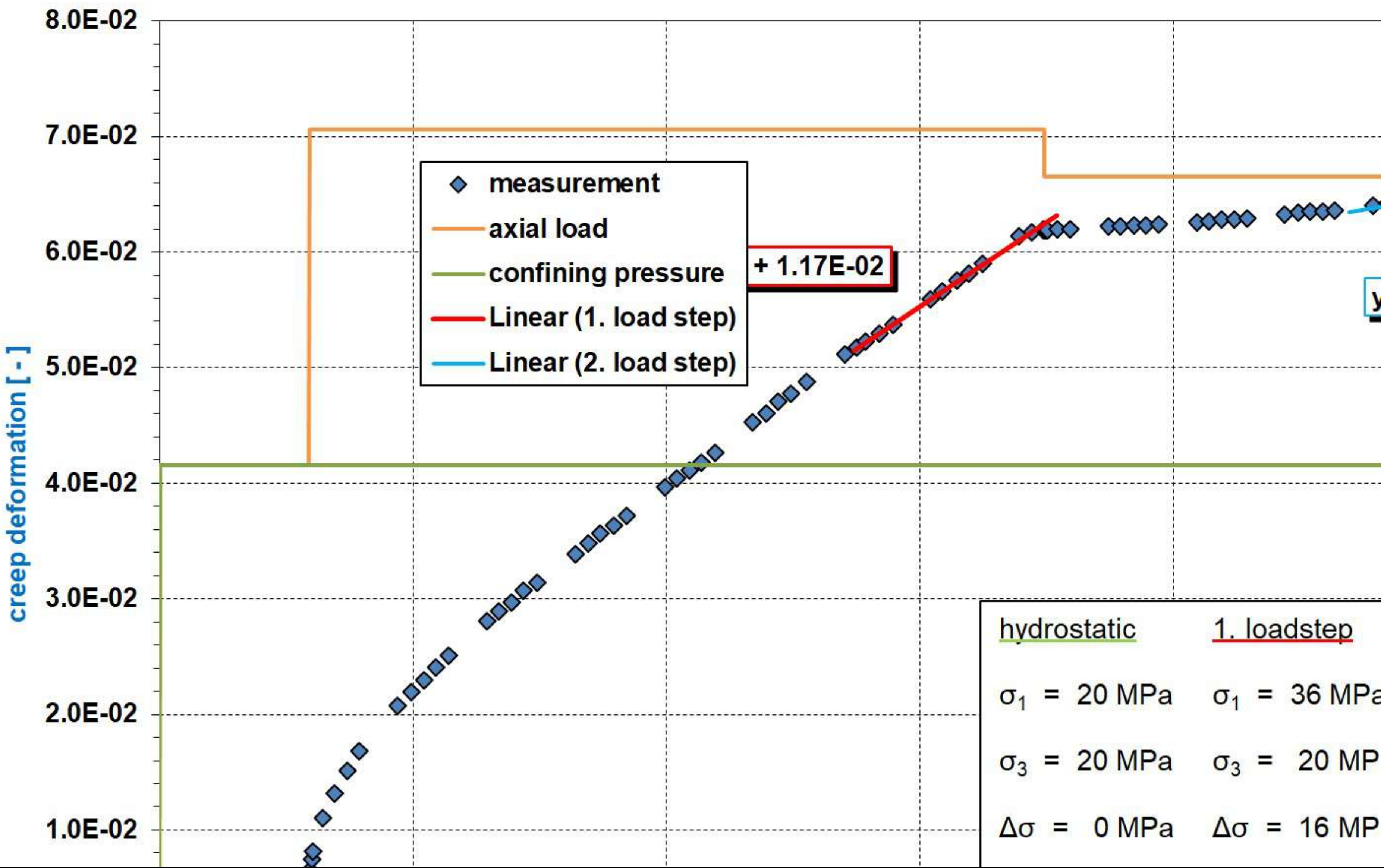
Triaxial creep test (TCC)

Unit – PRP (Pure Halite)

743/cx1030/TCC8

Appendix 220

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

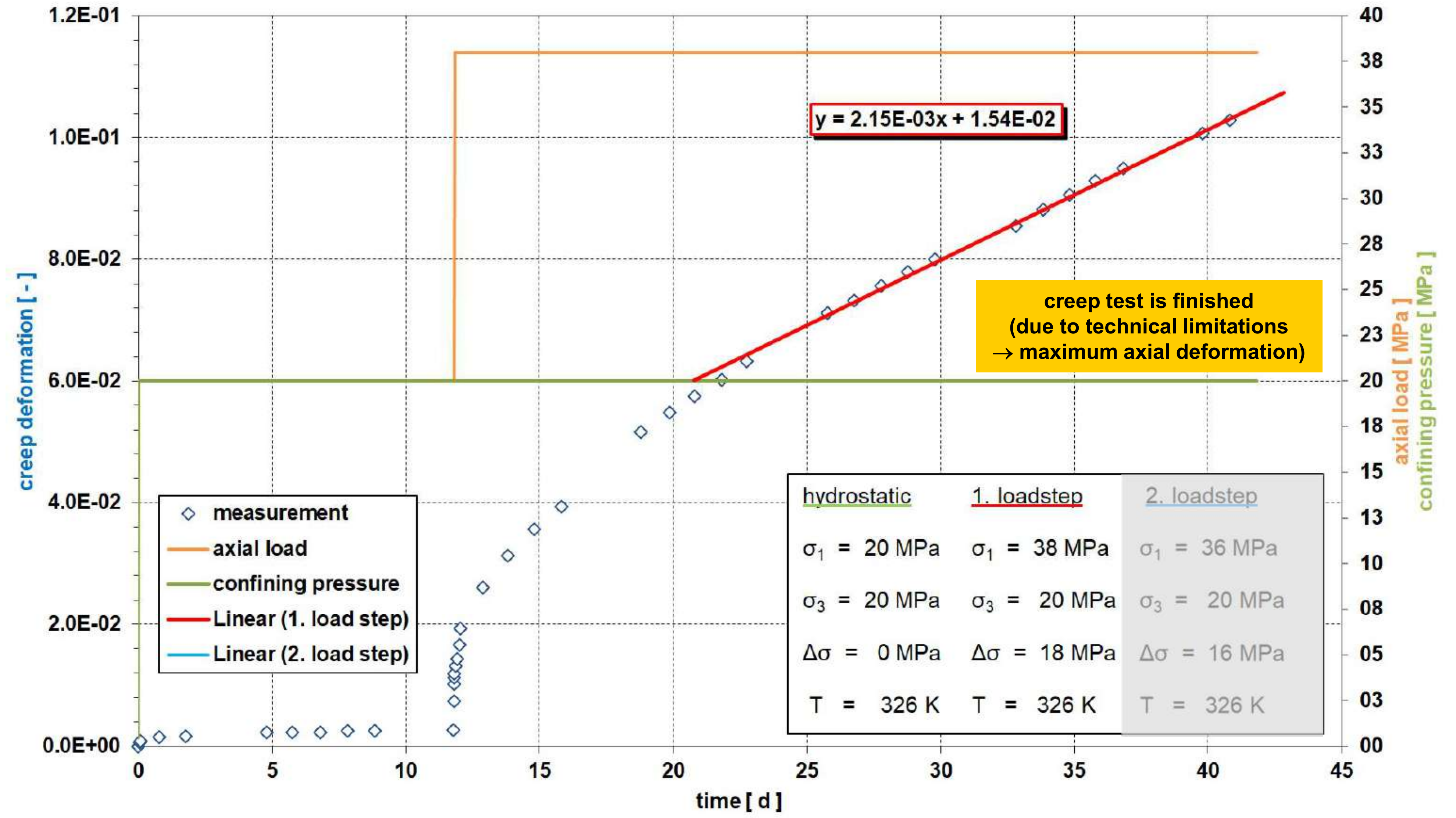
Triaxial creep test (TCC)

Unit – PRP (dirty salt; rock salt with impurities)

743/cx1102/TCC9

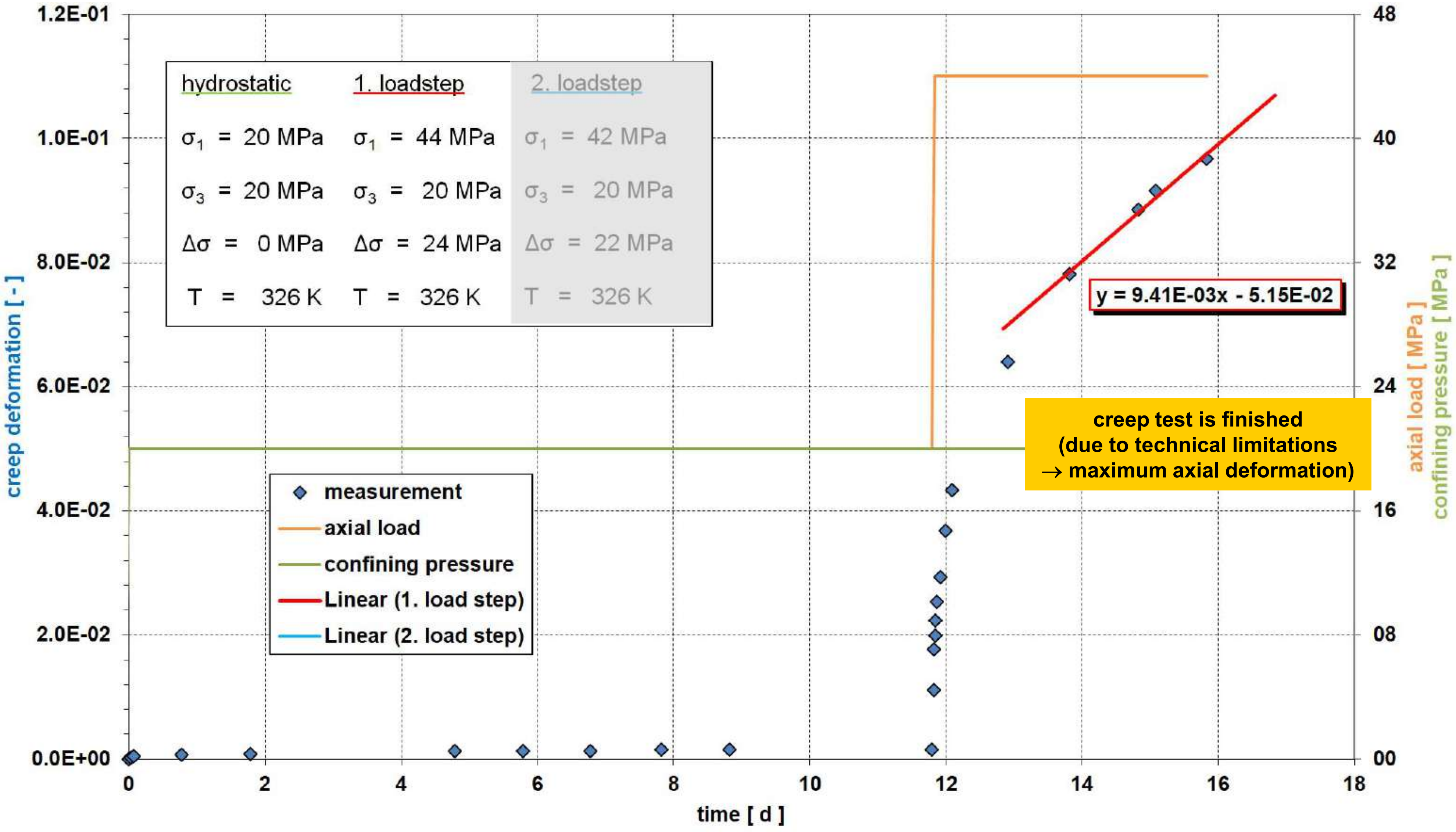
Appendix 221

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



project: 22/2021 Braskem - sample: 743/1102/TCC11 dirty salt

IfG INSTITUT FÜR GEBIRGSMECHANIK GMBH	**Triaxial creep test (TCC)** **Unit – PRP (dirty salt; rock salt with impurities)** 743/cx1102/TCC11	**Appendix 222** *B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"*



project: 22/2021 Braskem - sample: 743/1102/TCC12 dirty salt

INSTITUT FÜR GEBIRGSMECHANIK GMBH

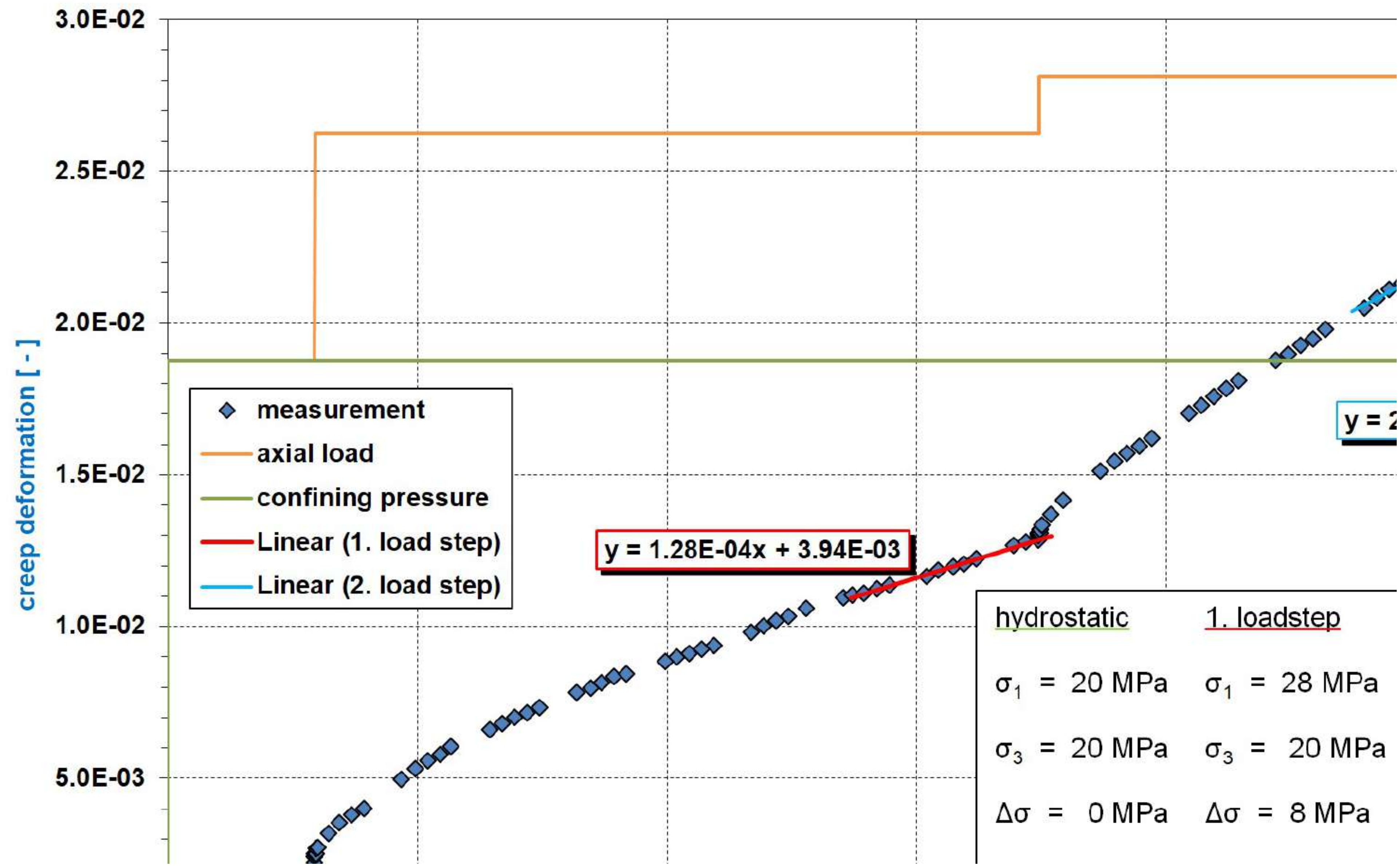
Triaxial creep test (TCC)

Unit – PRP (dirty salt; rock salt with impurities)

743/cx1102/TCC12

Appendix 223

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

Triaxial creep test (TCC)

Unit – PRP (dirty salt; rock salt with impurities)

743/cx1102/TCC13

Appendix 224

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

Test Types:	TC (nat) (2:1)	TC (Wet) (2:1)	Direct Tensile (2:1)	STT (Brazil) (1:1)	Shear (2:1)	Permeation (2:1)	Creep (18 cm)
Minimum size of "raw" core (lab should cut to fit the specimen size)	>26cm	>26cm	>26cm	>15cm	>26cm	>26cm	>20cm
MAR (Marituba Arenito)	9	9		6	6		
MAG (Marituba Argilito)	9	9		6	6		
MOS (Mosqueiro)	9	9		6	6		
MRT (Marituba II)	4						
IBU (Ibura)	9	9		6	6		
PAR (Poção Arenito)	9	9		6	6	3	
PCGL (Poção Conglomerado)	9	9		6	6	3	
PI (Poção Intercalado)	9	9		6	6	3	
PF (Poção Folhelho)	9	9		6	6	3	
TMS (Tabuleiro)	9	9	5	6	6	6	
PRP Pure Halite	7						8
PRP Intercalated Halite	8		5		6	6	4
PRP Shale from Halite	**6**		**5**		**6**		

INSTITUT FÜR GEBIRGSMECHANIK GMBH

Overview of planned tests

Unit – PRP (Shale from Halite)

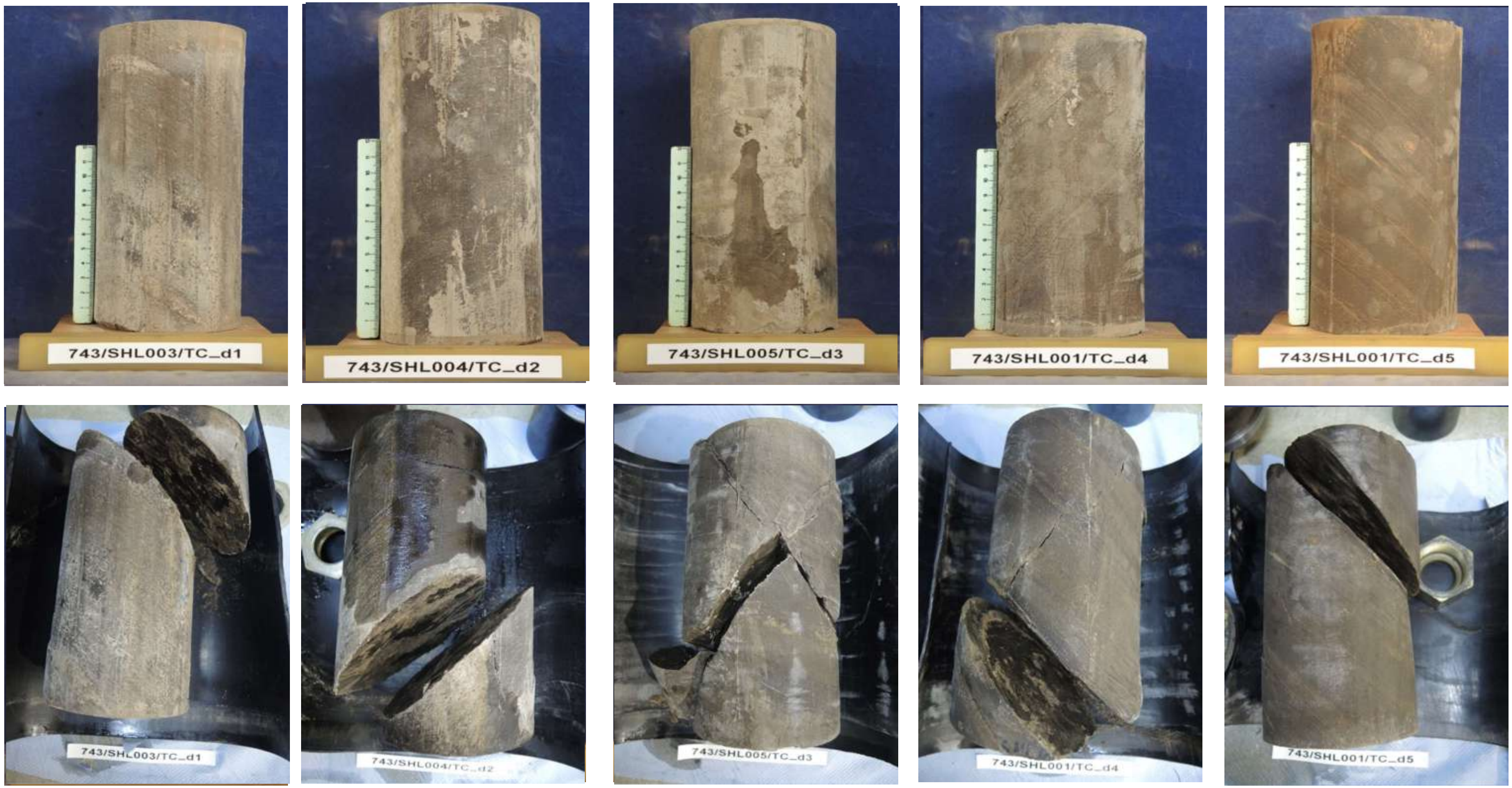
Appendix 225

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

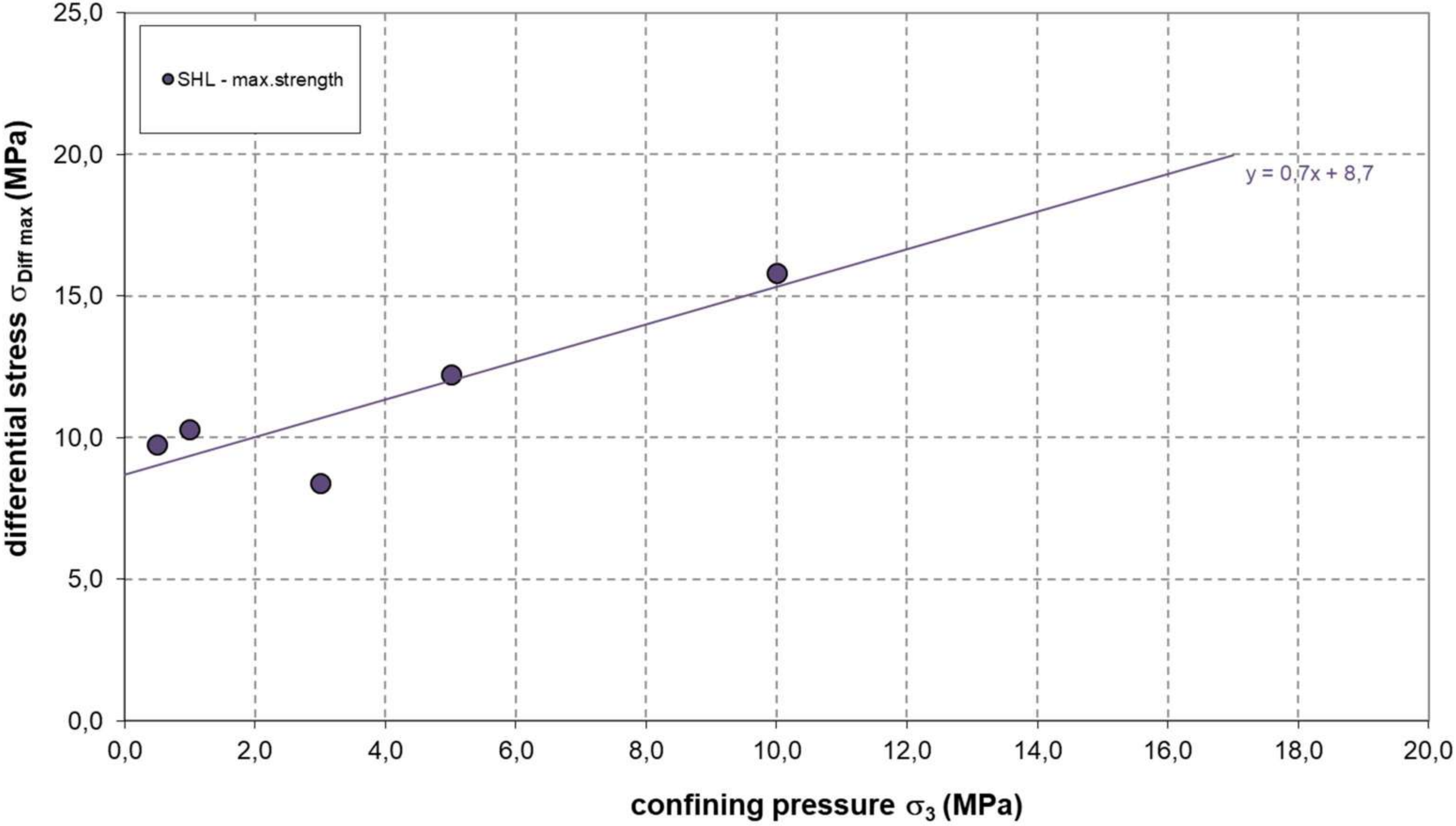
IfG - Lab-No.	743/SHL003/TC_d1	743/SHL004/TC_d2	743/SHL005/TC_d3	743/SHL001/TC_d4	743/SHL001/TC_d5
Rock Type / Unit	SHL	SHL	SHL	SHL	SHL
Sample	SHL_003	SHL_004	SHL_005	SHL_001	SHL_001
Depth (m)					
Length l (mm) =	198.105	197.508	200.715	197.745	199.798
Diameter d (mm) =	99.798	100.747	99.785	100.507	100.400
Ratio l_o/d_o =	1.99	1.96	2.01	1.97	1.99
Mass M (g) =	3036.80	3046.5	2951.5	3091.2	3003.3
Area A (cm^2) =	78.223	79.718	78.202	79.338	79.169
Volume V (cm^3) =	1549.63	1574.49	1569.64	1568.87	1581.79
Density ρ (g/cm^3) =	1.960	1.935	1.880	1.970	1.899
US L (h) - p					
US Q1 (a/c) - p					
US Q2 (b/d) - p					
US L (h) - s					
US L (h) - p(s)					
$V_{p\text{-axial}}$ (km/s) =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
$V_{p\text{-radial: a-c}}$ (km/s) =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
$V_{p\text{-radial: b-d}}$ (km/s) =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
$V_{s\text{-axial}}$ (km/s) =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
E_d (GPa) =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
K_d (GPa) =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
G_d (GPa) =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
ν_d =	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	TC	TC	TC	TC	TC
Temp. (°C)	23	23	23	23	23
σ_3 (MPa) =	0.5	1.0	3.0	5.0	10.0
σ_{Dil} (MPa) =	9.7	10.3	6.6	12.1	13.0
ΔV_{Dil} (%) =	-0.48	-0.69	-1.82	-1.67	-1.55
ε_{Dil} (%) =	0.96	1.24	10.94	10.88	9.19
σ_{Fail} (MPa) =	9.8	10.3	8.4	12.2	15.8
ΔV_{Fail} (%) =	-0.48	-0.69	-1.61	-1.68	-1.44
ε_{Fail} (%) =	0.99	1.23	5.45	11.02	3.78
σ_{1Fail} (MPa) =	10.27	11.28	11.39	17.23	25.81
α (°) =	65	65	65	65	65
σ_n (MPa) =	2.25	2.84	4.50	7.18	12.82
τ (MPa) =	3.74	3.94	3.21	4.68	6.05
ϕ=			14.4		
C=			3.4		

BEFORE:

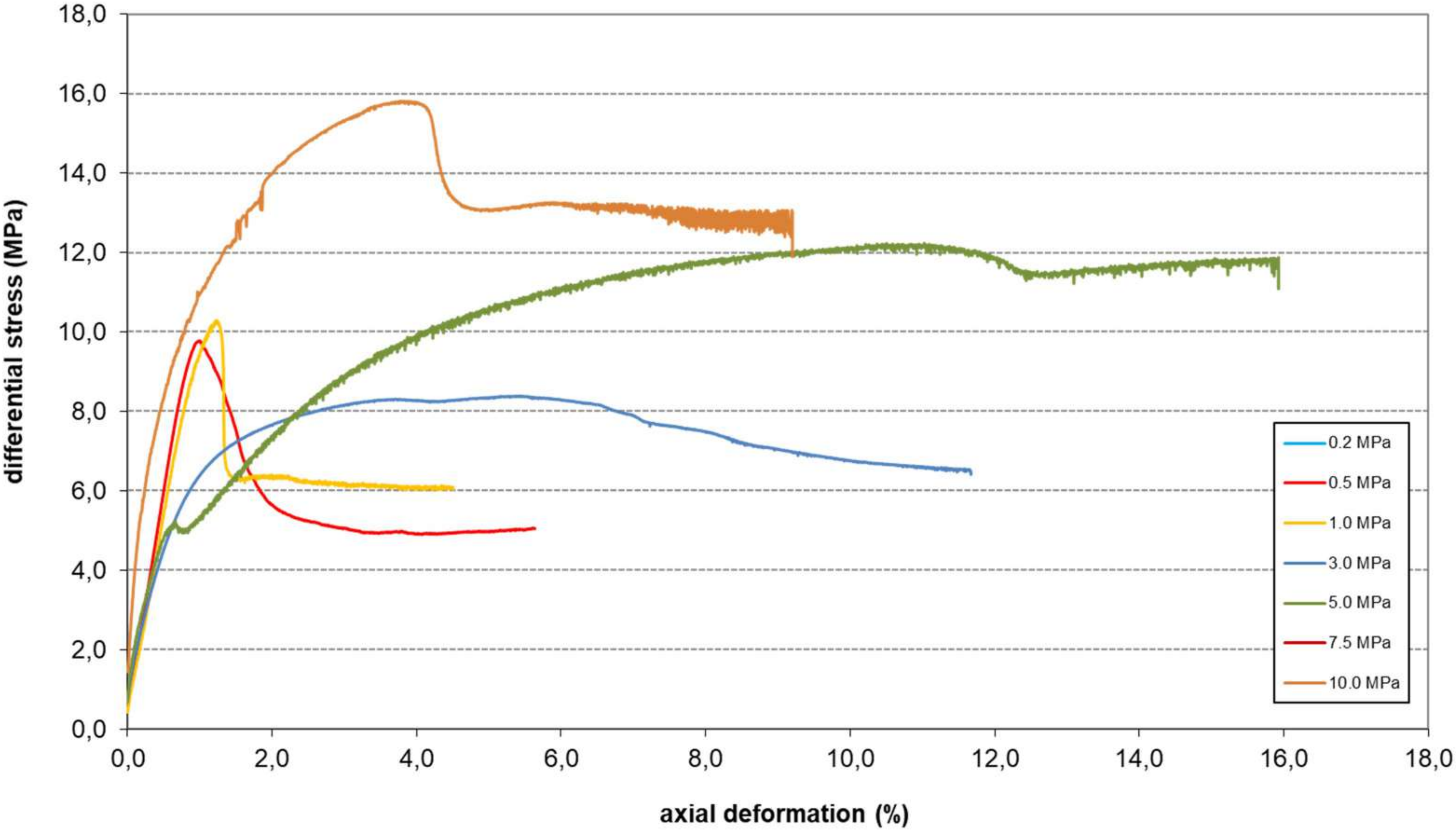
AFTER:



σ_3 = 0.5 MPa | σ_3 = 1.0 MPa | σ_3 = 3.0 MPa | σ_3 = 5.0 MPa | σ_3 = 10.0 MPa



SHL - max.strength
y = 0,7x + 8,7
differential stress $\sigma_{Diff\ max}$ (MPa)
confining pressure σ_3 (MPa)
25,0
20,0
15,0
10,0
5,0
0,0
0,0
2,0
4,0
6,0
8,0
10,0
12,0
14,0
16,0
18,0
20,0



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

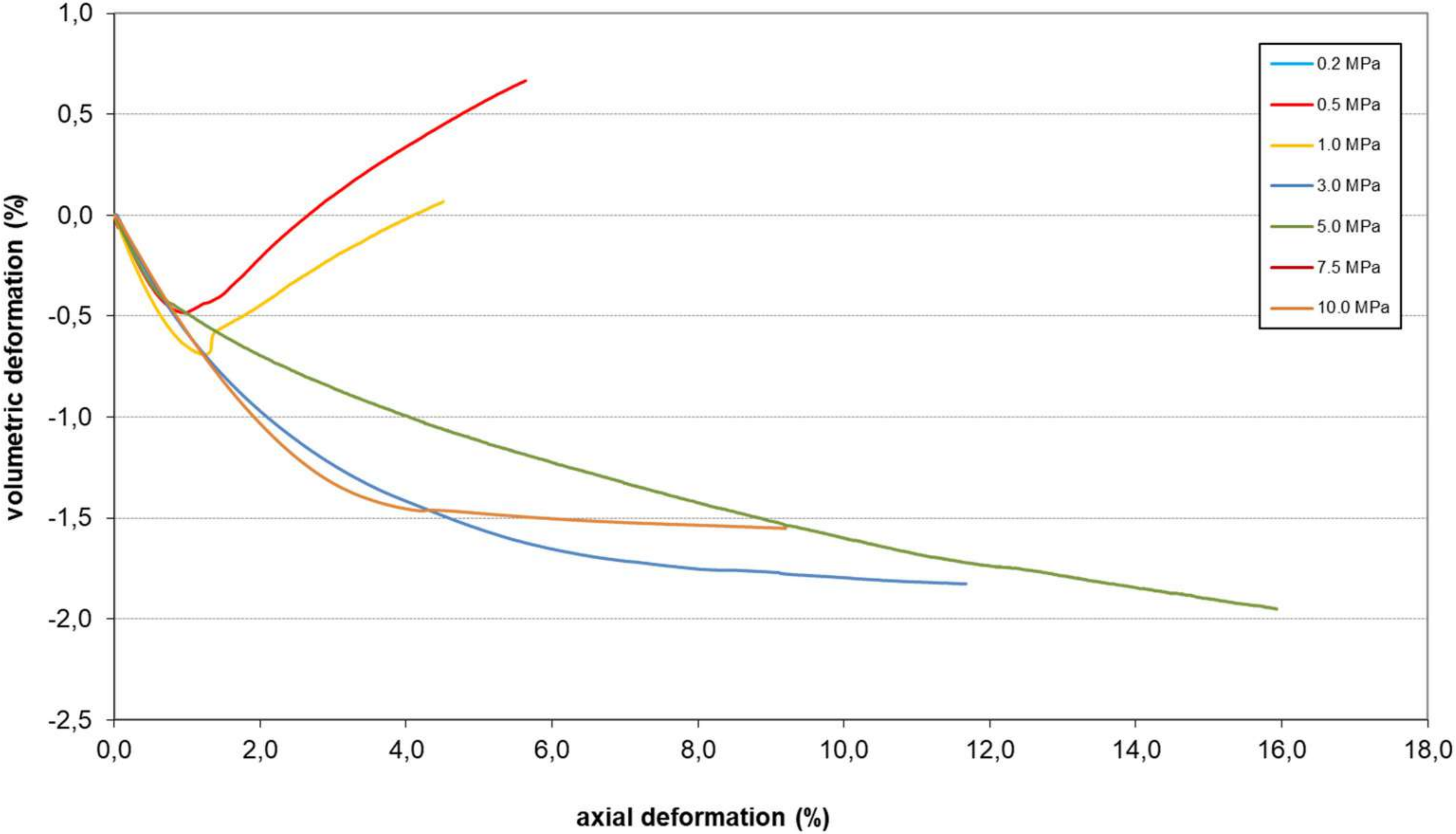
Triaxial strength tests (TC_nat)

Unit – PRP (Shale from Halite)

→ stress-strain curves of all tests

Appendix 229

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

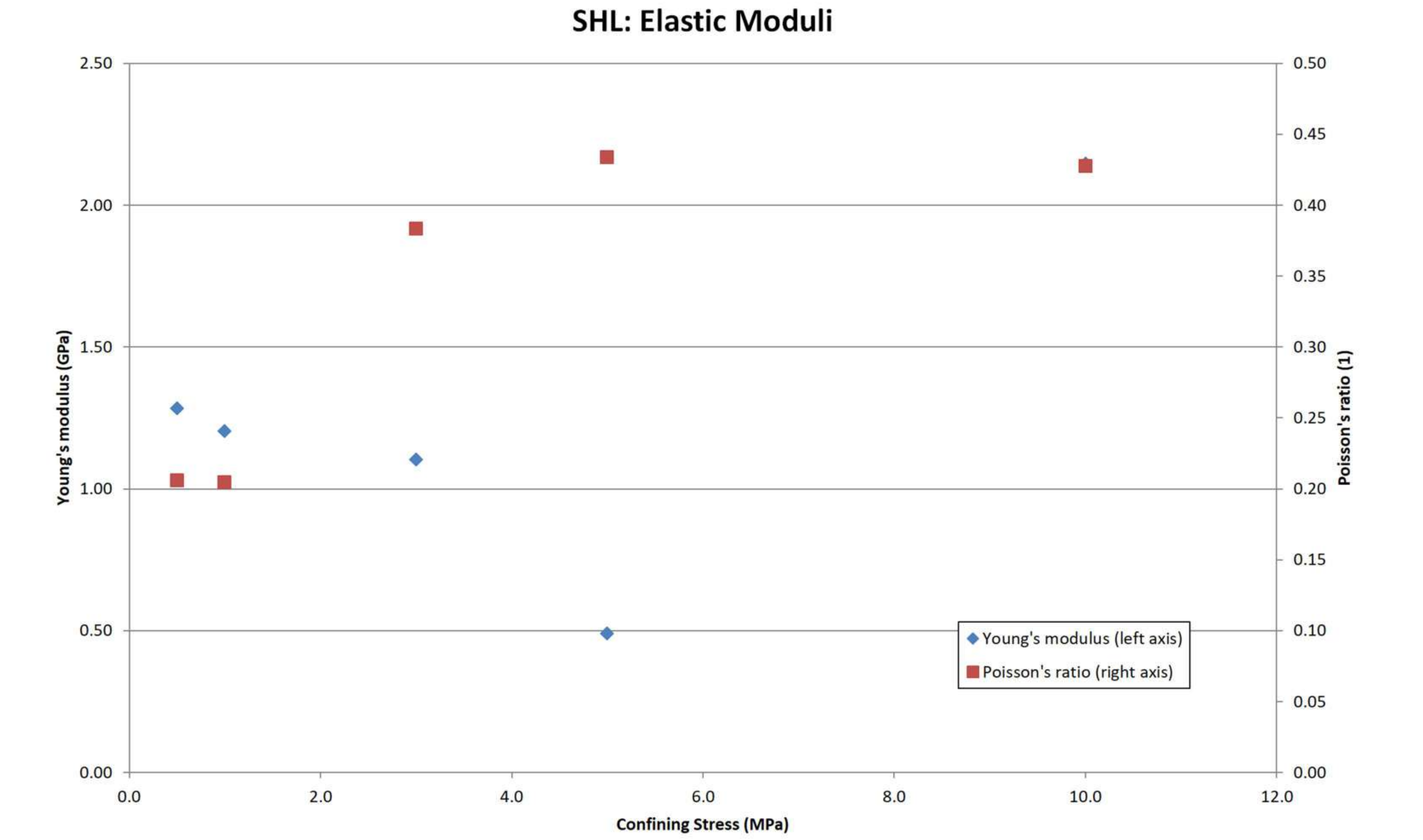
Triaxial strength tests (TC_nat)

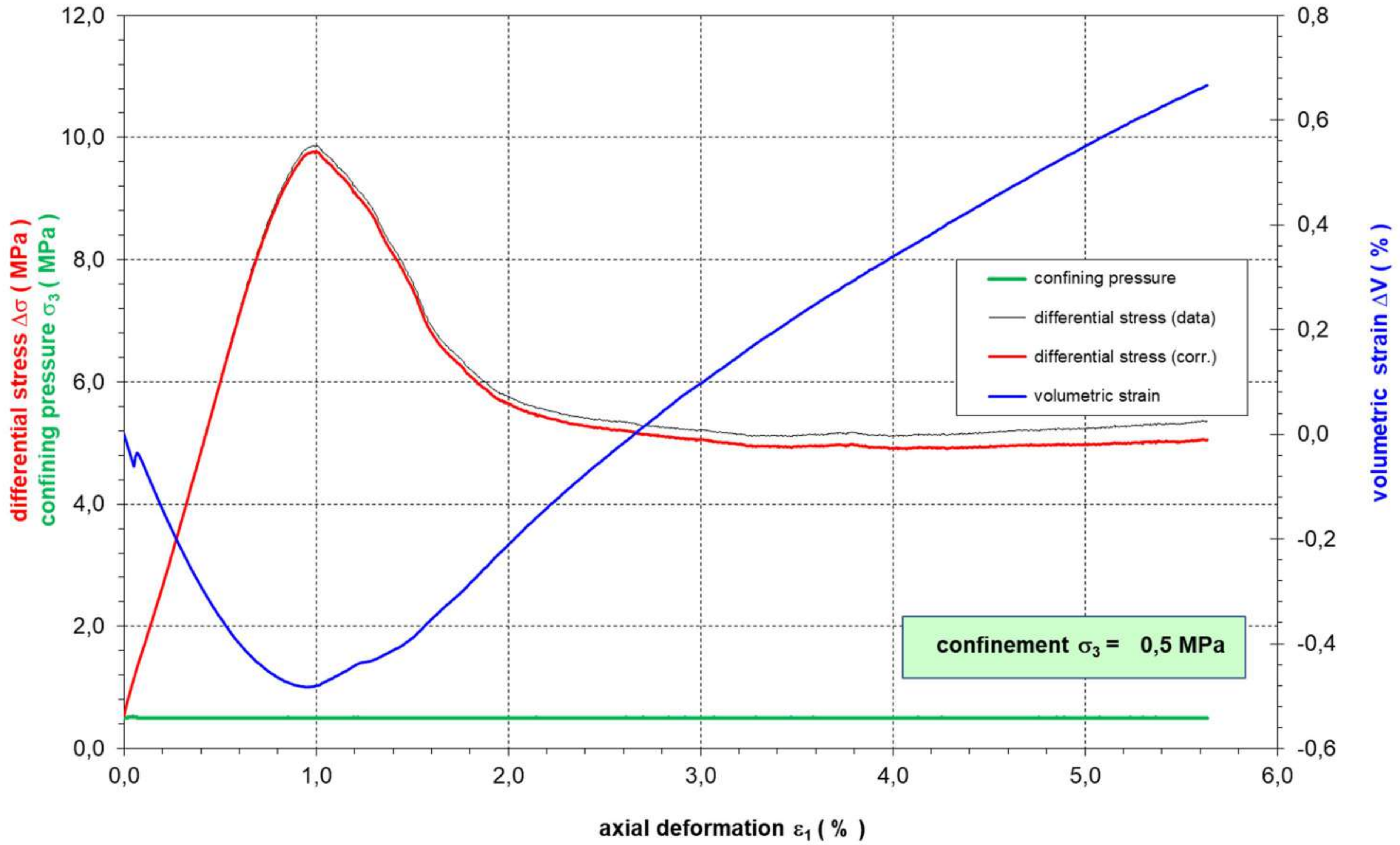
Unit – PRP (Shale from Halite)

→ volumetric strain vs. axial deformation; dilatancy curves

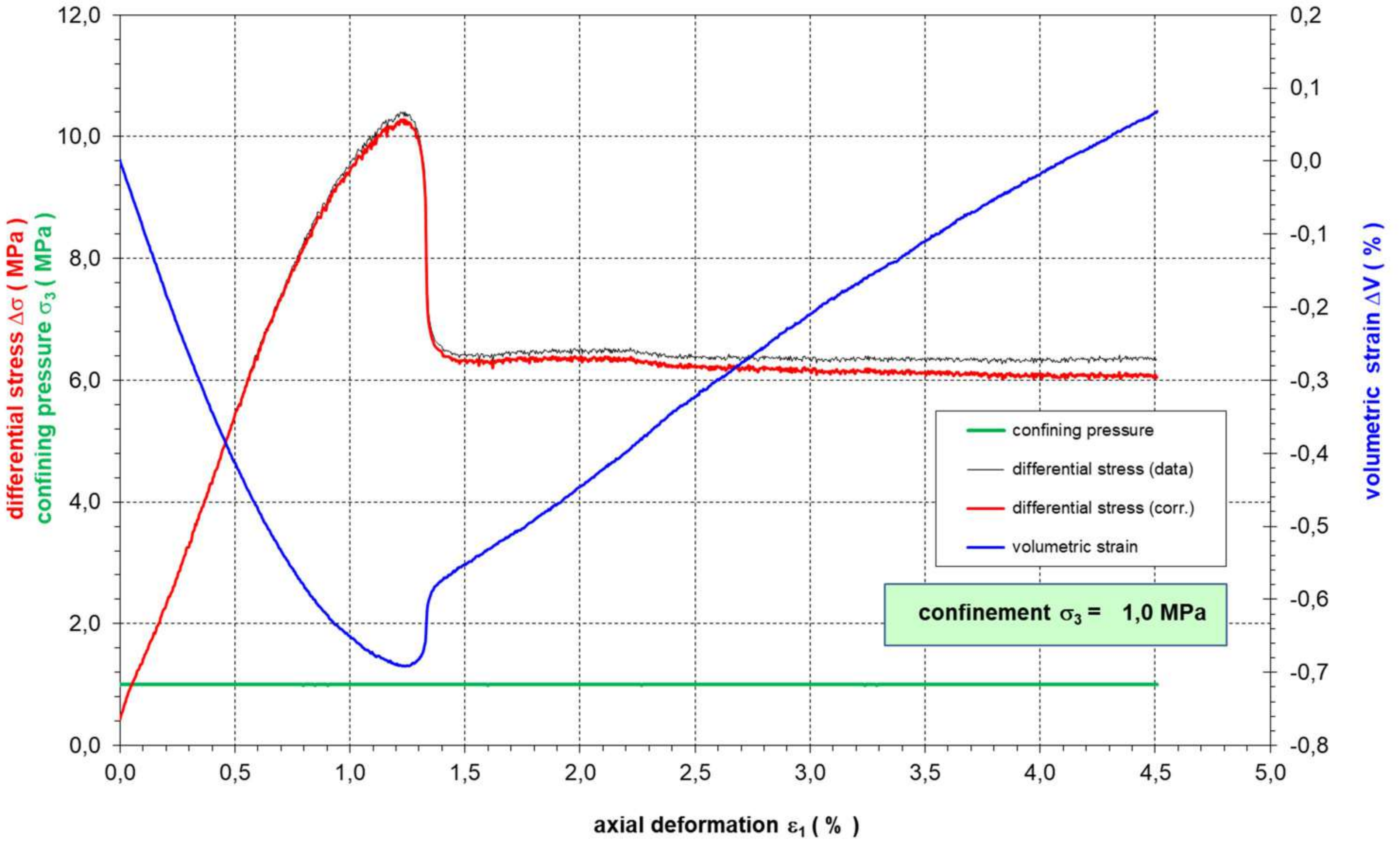
Appendix 230

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"


SHL: Elastic Moduli
Young's modulus (GPa)
Poisson's ratio (1)
Confining Stress (MPa)
0.00
0.50
1.00
1.50
2.00
2.50
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Young's modulus (left axis)
Poisson's ratio (right axis)



12,0
10,0
8,0
6,0
4,0
2,0
0,0
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
0,0
1,0
2,0
3,0
4,0
5,0
6,0
differential stress Δσ (MPa)
confining pressure σ3 (MPa)
volumetric strain ΔV (%)
axial deformation ε1 (%)
confining pressure
differential stress (data)
differential stress (corr.)
volumetric strain
confinement σ3 = 0,5 MPa



INSTITUT FÜR GEBIRGSMECHANIK GMBH

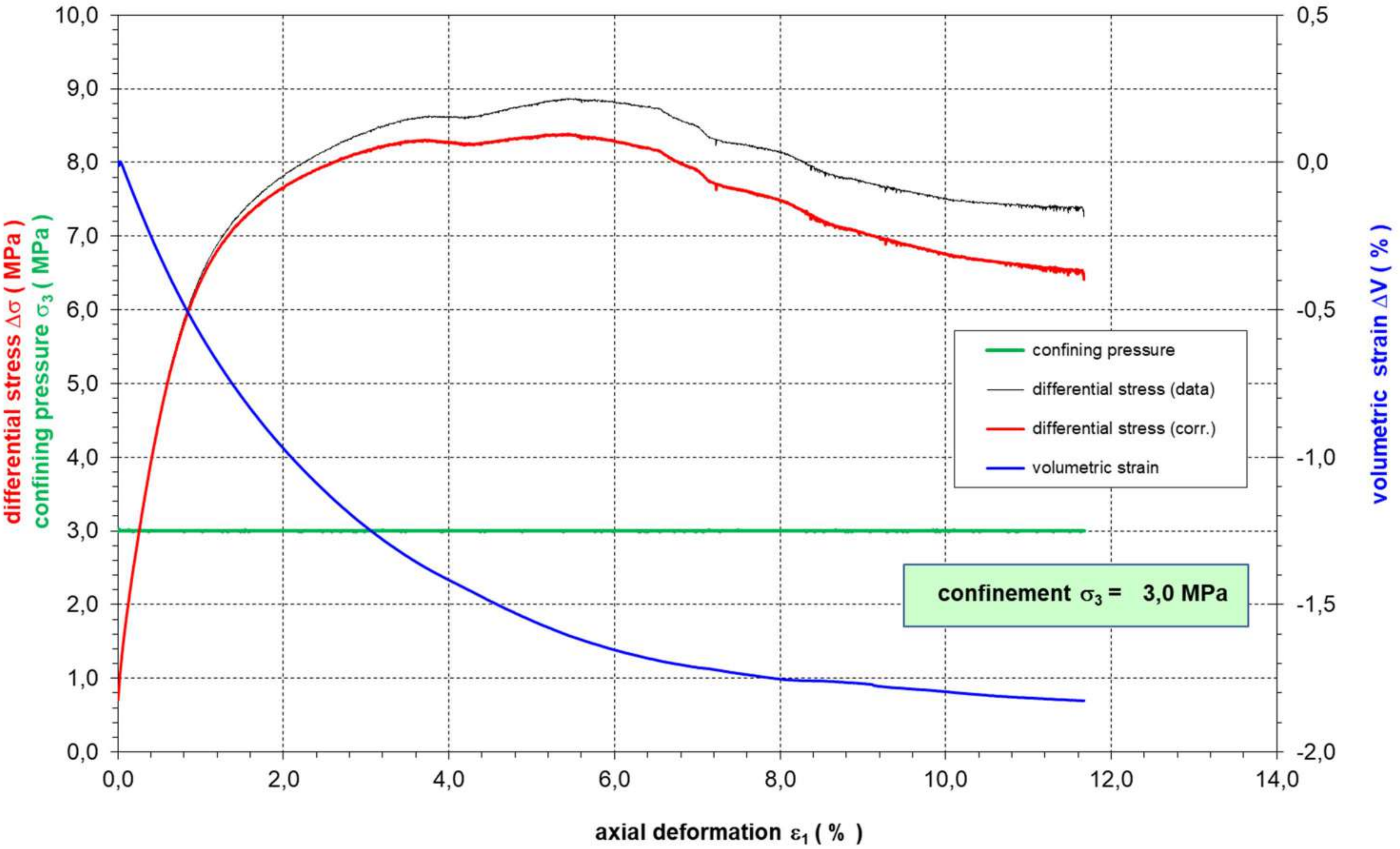
Triaxial strength test (TC_nat)

Unit – PRP (Shale from Halite)

→ stress-strain behavior; sample 743/SHL004/TC_d2

Appendix 233

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

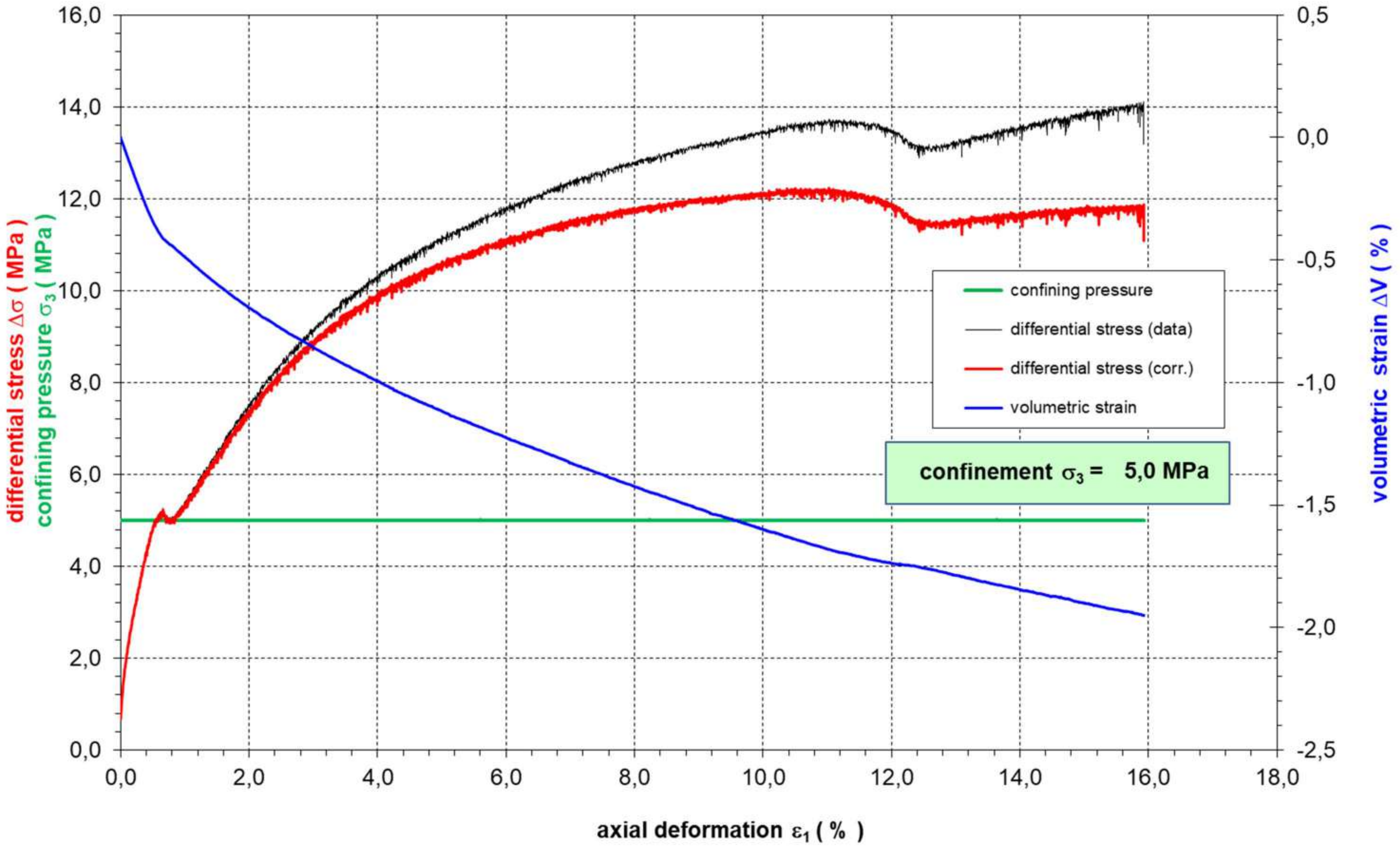
Triaxial strength test (TC_nat)

Unit – PRP (Shale from Halite)

→ stress-strain behavior; sample 743/SHL005/TC_d3

Appendix 234

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

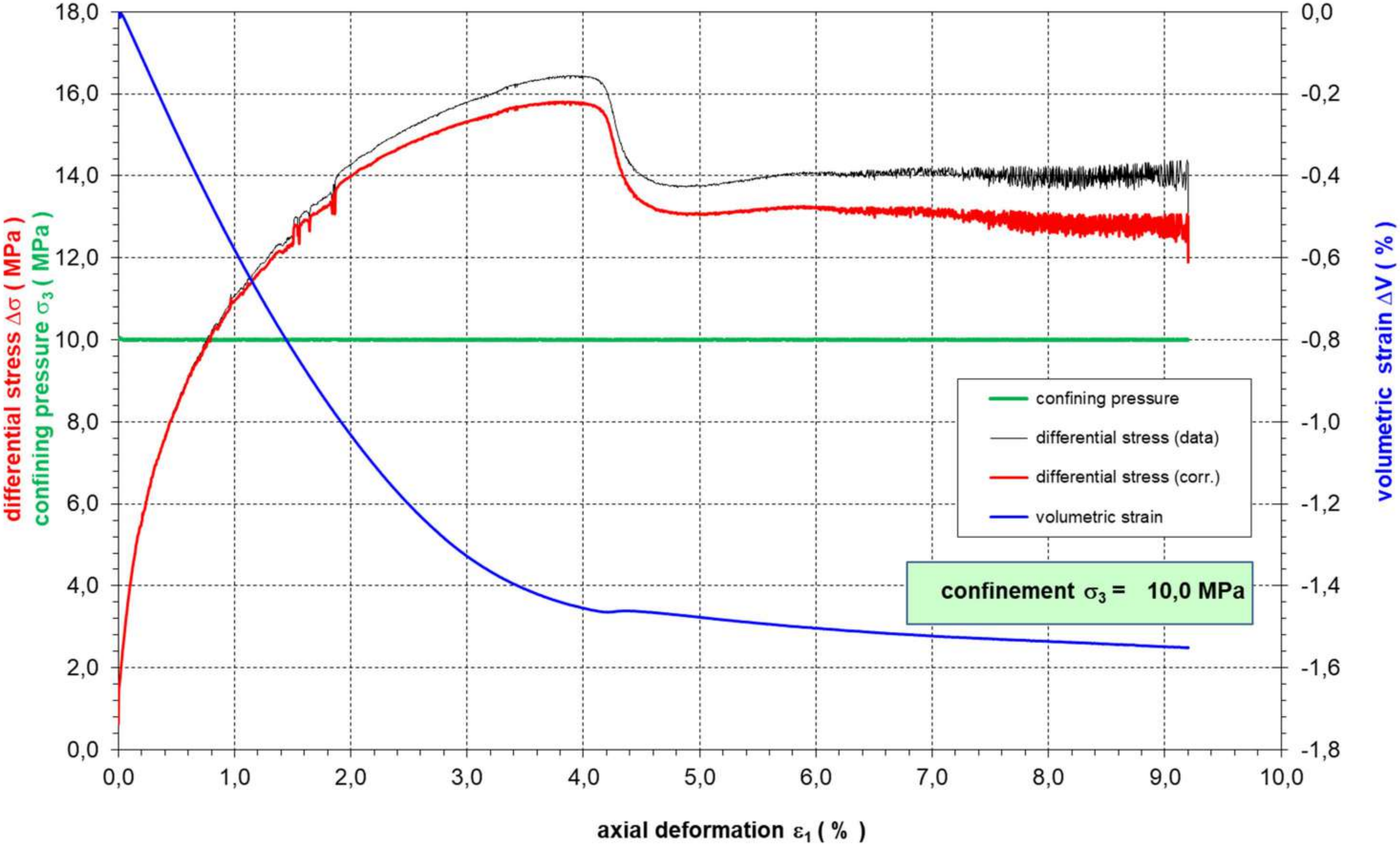
Triaxial strength test (TC_nat)

Unit – PRP (Shale from Halite)

→ stress-strain behavior; sample 743/SHL001/TC_d4

Appendix 235

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

Triaxial strength test (TC_nat)

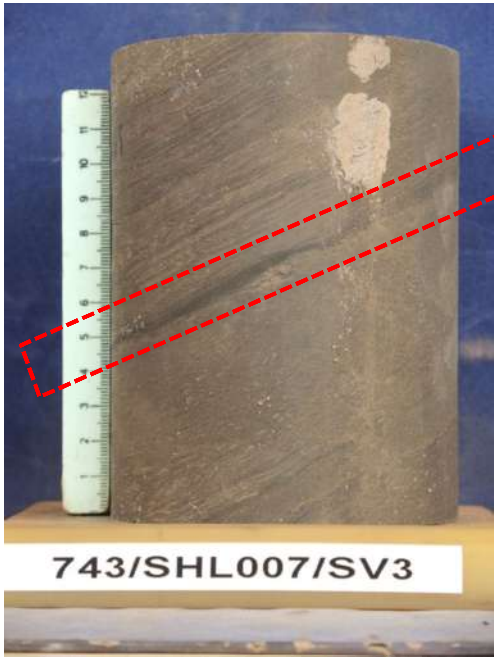
Unit – PRP (Shale from Halite)

→ stress-strain behavior; sample 743/HL001/TC_d5

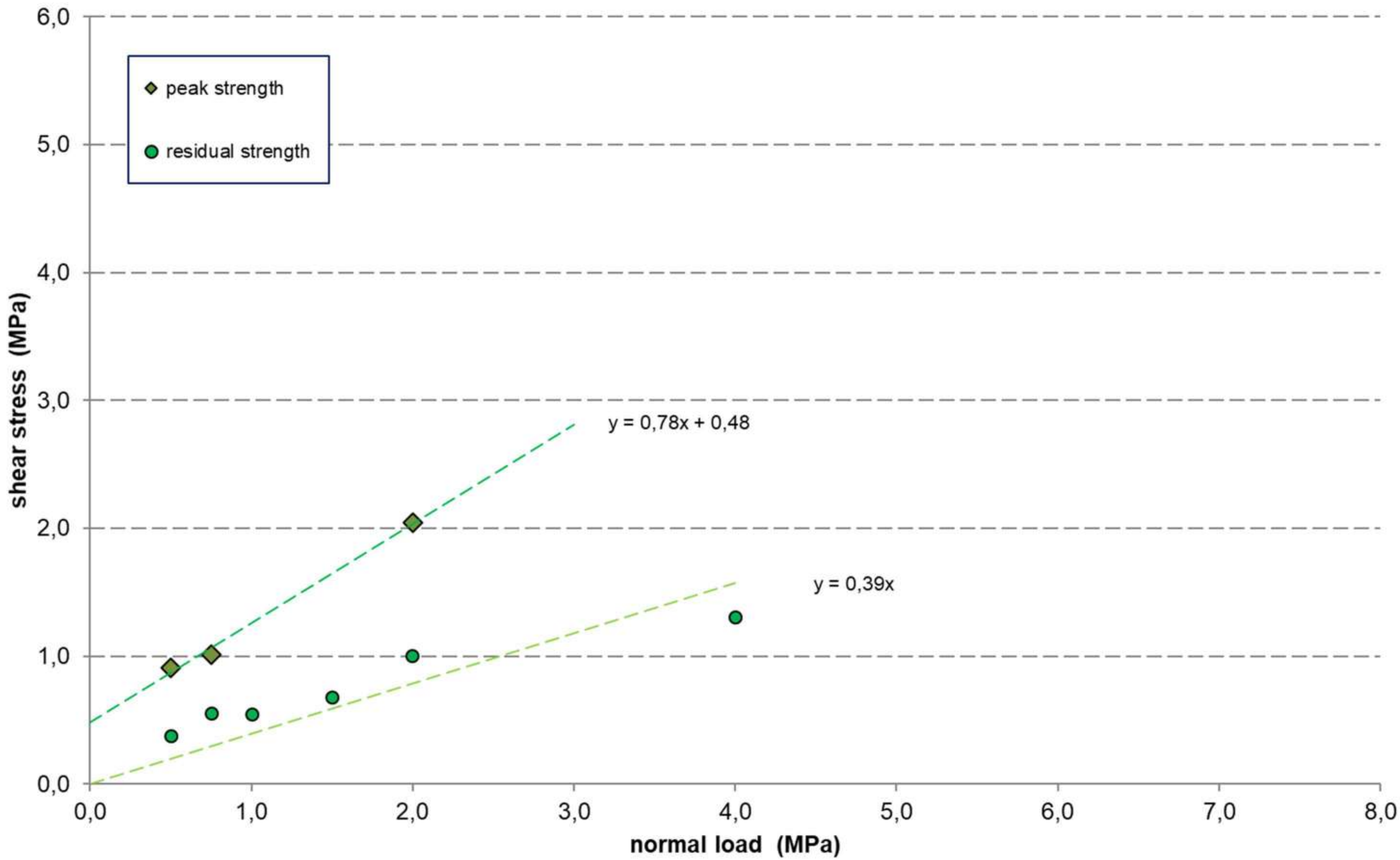
Appendix 236

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

BEFORE:



AFTER:



INSTITUT FÜR
GEBIRGSMECHANIK
GMBH

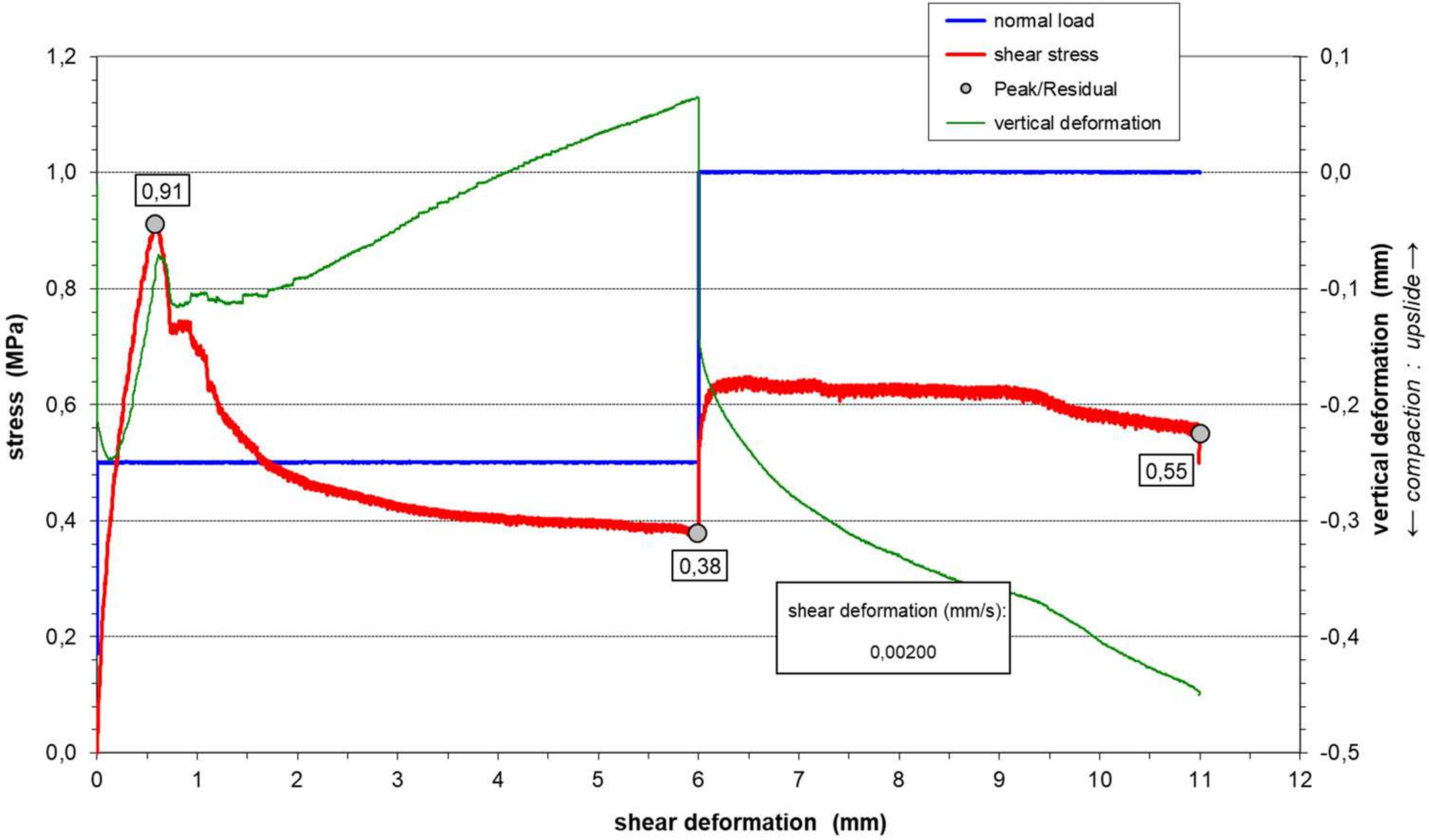
Direct shear tests (DST)

Unit – PRP (Shale from Halite)

→ peak and residual strength values

Appendix 238

B IfG 22/2021
"Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

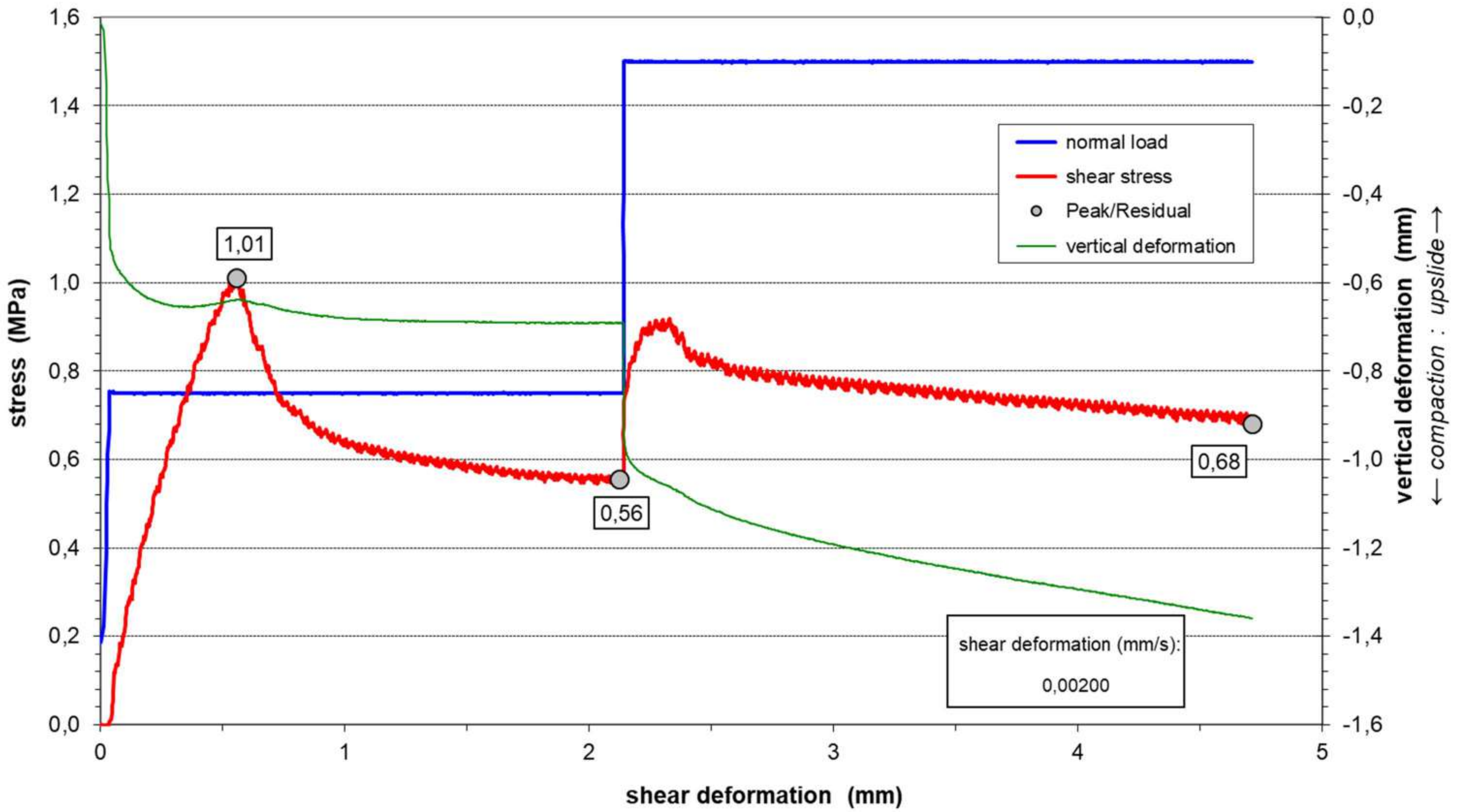
Direct shear test (DST)

Unit – PRP (Shale from Halite)

743/SHL001/SV1

Appendix 239

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR GEBIRGSMECHANIK GMBH

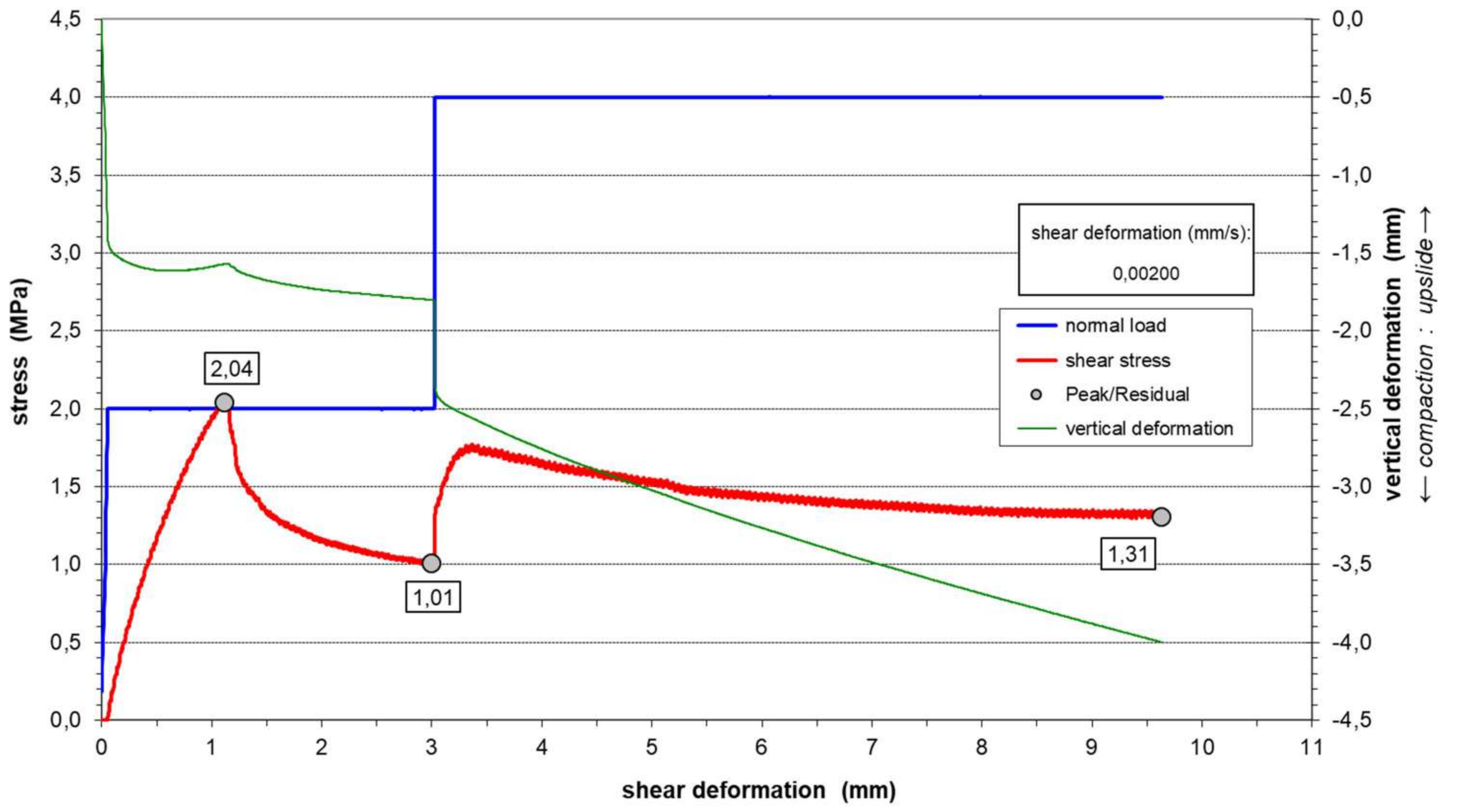
Direct shear test (DST)

Unit – PRP (Shale from Halite)

743/SHL007/SV2

Appendix 240

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"



INSTITUT FÜR **GEBIRGSMECHANIK** GMBH

Direct shear test (DST)

Unit – PRP (Shale from Halite)

743/SHL007/SV3

Appendix 241

B IfG 22/2021 "Rock Mechanical Investigations – Maceio – BRASKEM"

	core	TC_nat				DTT (direct tensile)	STT (splitting tensile)	Shear (DST)	
	bulk density ρ	Dynamic Young's modulus	Dynamic Poisson's ratio	Cohesion C	Friction angle ϕ	σ_{DTT}	σ_{STT}	cohesion c	friction angle ϕ
	(g/cm³)	(GPa)	(1)	(MPa)	(°)	(MPa)	(MPa)	(MPa)	(°)
MAR (Marituba Arenito)	**2.16**			**0.7**	**27.9**				
MAG (Marituba Argilito)	**1.99**			**0.8**	**24.2**				
MO (Mosqueiro)	**2.2**			**2.2**	**33.2**				
MRT (Marituba II)	**2.15**			**1.4**	**25.3**				
IBU (Ibura)	**2.21**			**9.8**	**6.5**				
PAR (Poção Arenito)		**6.4**	**0.21**	**2.4**	**22.5**				
PCG (Poção Conglomerado)		**8.2**	**0.31**	**2.9**	**22.4**				
PI (Poção Intercalado)				**2.0**	**28.3**				
PF (Poção Folhelho)		**8.9**	**0.14**	**4.5**	**13.0**				
TMS (Tabuleiro)	**2.3**	**6.5**	**0.14**	**7.5**	**19.5**	**0.10**	**2.20**	**1.12**	**41**
PRP Pure Halite	**2.14**	**32.7**	**0.23**						
SHL Shale from Halite	**1.93**	**3.1**	**0.20**	**3.4**	**14.4**			**0.48**	**38**