

P-04-262

Oskarshamn site investigation

Borehole KLX04A

Triaxial compression test of intact rock

Lars Jacobsson
SP Swedish National Testing and Research Institute

October 2004

Svensk Kärnbränslehantering AB

Swedish Nuclear Fuel
and Waste Management Co
Box 5864

SE-102 40 Stockholm Sweden

Tel 08-459 84 00
+46 8 459 84 00

Fax 08-661 57 19
+46 8 661 57 19



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Keywords: Rock mechanics, Triaxial compression test, Elasticity parameters, Stress-strain curve, Post-failure behaviour.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

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Abstract

Triaxial compression tests with constant confining pressure, containing the complete loading response beyond compressive failure, so called post-failure tests, were carried out on 14 water saturated specimens of intact rock from borehole KLX04A in Laxemar. The cylindrical specimens were taken from drill cores at three depth levels ranging between 307–308 m, 565–566 m and 750–751 m. Moreover, the rock type was mapped as Ävrö granite. The elastic properties, represented by the Young's modulus and the Poisson ratio, and the compressive strength were deduced from these tests. The wet density of the specimens were determined before the mechanical tests. The specimens were documented by photographing the specimens before and after the mechanical testing.

The measured densities for the water saturated specimens were in the range 2,650–2,740 kg/m³, which yields a mean value of 2 709 kg/m³. Five confining pressure levels were used, 2, 7, 10, 15 and 20 MPa, and the peak values of the axial compressive stress were in the range 187.5–346.8 MPa. The elastic parameters were determined at load corresponding to 50% of the failure load and it was found that Young's modulus was in the range 60.8–76.2 GPa with a mean value of 69.7 GPa and the Poisson ratio was in the range of 0.15–0.20 with a mean value of 0.18. It was seen from the mechanical tests that the material in the specimens responded in a brittle way.

Sammanfattning

Triaxiella kompressionsprov med belastning upp till brott och efter brott, så kallade ”post-failure tests”, har genomförts på 14 stycken vattenmättade cylindriska provobjekt av intakt berg. Provobjekten har tagits från en borrhärla från borrhål KLX04A i Laxemar vid tre djupnivåer 307–308 m, 565–566 m och 750–751 m. Bergtypen vid dessa nivåer var Ävrö granit. De elastiska egenskaperna, representerade av elasticitetsmodulen och Poissons tal, har bestämts ur försöken. Bergmaterialets densitet i vått tillstånd hos proverna mättes upp före de mekaniska proven. Provobjekten fotograferades före och efter de mekaniska proven.

Den uppmätta densiteten hos de vattenmättade proven var mellan 2 650–2 740 kg/m³ med ett medelvärde på 2 709 kg/m³. Fem olika celltryck användes vid triaxialproven 2, 7, 10, 15 och 20 MPa och toppvärdena för den axiella kompressiva spänningen låg mellan 187,5–346,8 MPa. De elastiska parametrarna bestämdes vid en last motsvarande 50 % av topplasten vilket gav en elasticitetsmodul mellan 60,8–76,2 GPa med ett medelvärde på 69,7 GPa och Poissons tal mellan 0,15–0,20 med ett medelvärde på 0,18. Vid belastningsförsöken kunde man se att materialet i provobjekten hade ett sprött beteende.

Contents

1	Introduction	7
2	Objective and scope	9
3	Equipment	11
3.1	Specimen preparation and density measurement	11
3.2	Mechanical testing	11
4	Execution	13
4.1	Description of the specimens	13
4.2	Specimen preparation and density measurement	14
4.3	Mechanical testing	14
4.4	Data handling	15
4.5	Analyses and interpretation	15
5	Results	17
5.1	Description and presentation of the specimen	17
5.2	Results for the entire test series	46
5.3	Discussion	49
	References	51
	Appendix A	53
	Appendix B	55

1 Introduction

Triaxial compression tests, with loading beyond the failure point into the post-failure regime, have been conducted on water-saturated specimens sampled from borehole KLX04A in Laxemar, see map in Figure 1-1. These tests belong to one of the activities performed as part of the site investigation in the Laxemar area lead by the Swedish Nuclear Fuel and Waste Management Co (SKB). The tests were carried out in the material and rock mechanics laboratories at the Department of Building Technology and Mechanics at the Swedish National Testing and Research Institute (SP). All work is carried out in accordance with the activity plan AP PS 400-04-073 (SKB internal controlling document) and is controlled by SP-QD 13.1 (SP internal quality document).

SKB supplied SP with rock cores and they arrived at SP in August 2004 and were tested during October 2004. Cylindrical specimens were cut from the cores and selected based on the preliminary core logging with the strategy to primarily investigate the properties of the dominant rock type. The method description SKB MD 190.003, version 2.0, (SKB internal controlling document) was followed both for the sampling and for the triaxial compression tests and the method description SKB MD 160.002, version 2.0, (SKB internal controlling

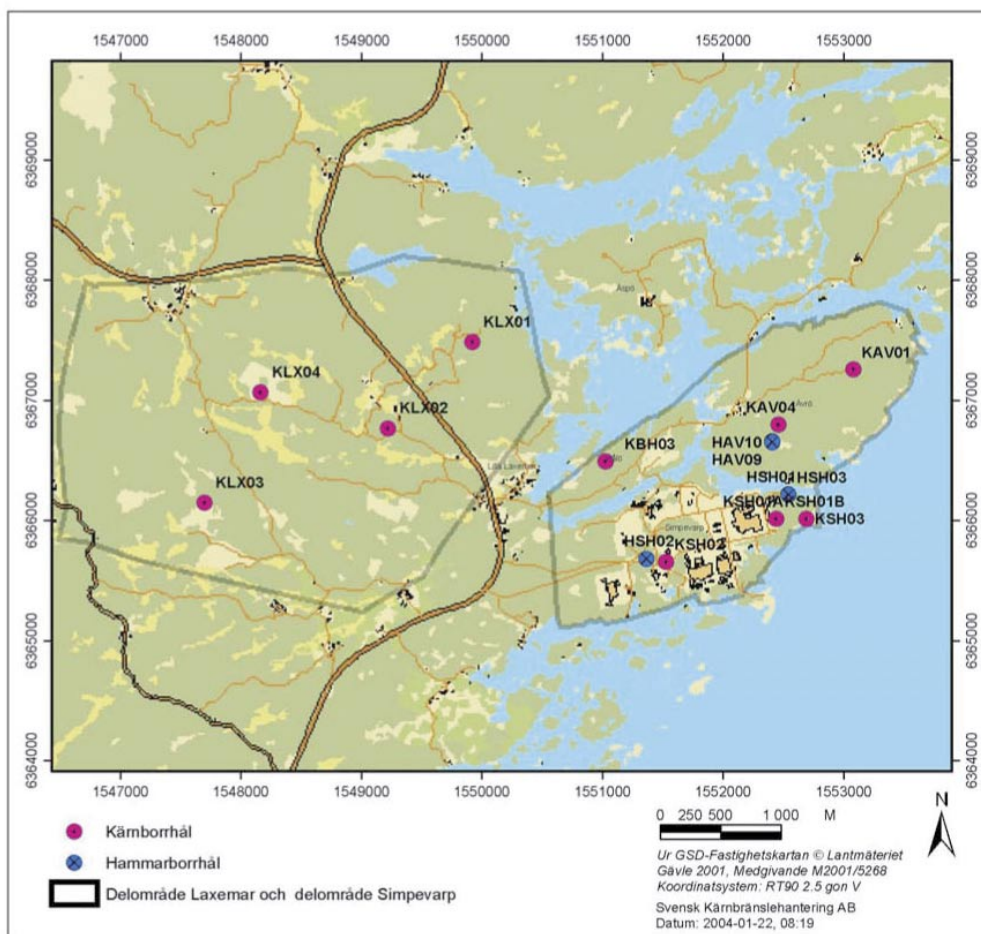


Figure 1-1. Location of the borehole KLX04A at the Laxemar site.

document) was followed when the density was determined. As to the specimen preparation, the end surfaces on the specimens were grinded in order to comply with the required shape tolerances and kept stored in water, with a minimum of 7 days, up to testing. This yields a water saturation, which is intended to resemble the in-situ moisture condition. The density was determined on each specimen and the triaxial compression tests were carried out at this moisture condition at different confining pressures. The specimens were photographed before and after the mechanical testing.

The triaxial compression tests were carried out using radial strain as the feed back signal in order to obtain the complete response in the post-failure regime on brittle specimens as is described in the method description SKB MD 190.003, version 2.0, (SKB internal controlling document) and in the ISRM suggested method /1/. The axial ε_a and radial strain ε_r together with the axial stress σ_a were recorded during the test. The peak value of the axial compressive stress σ_c was determined at each test. Furthermore, two elasticity parameters, Young's modulus E and Poisson ratio ν , were deduced from the tangent properties at 50% of the peak load. Diagrams with the volumetric and crack volumetric strain versus axial stress are reported. These diagrams can be used to determine crack initiation stress σ_i and the crack damage stress σ_d , cf /2, 3/.

2 Objective and scope

The purpose of the testing is to determine the compressive strength and the elastic properties, represented by the Young's modulus and the Poisson ratio, of confined cylindrical intact rock cores at different confining pressures. Moreover, the specimens have a water content corresponding to the in-situ conditions. The loading is carried out into the post-failure regime in order to study the mechanical behaviour of the rock after cracking and thereby be able to determine the brittleness and residual strength. The specimens are from the borehole KLX04A, which has a bore depth of 1,000 m.

The results from the tests are going to be used in the site descriptive rock mechanics model, which will be established for the candidate area selected for site investigations at Laxemar.

3 Equipment

3.1 Specimen preparation and density measurement

A circular saw with a diamond blade was used to cut the specimens to their final lengths. The surfaces were then grinded after cutting in a grinding machine in order to achieve a high-quality surface for the axial loading that complies with the required tolerances. The measurements of the specimen dimensions were made with a sliding calliper. Furthermore, the tolerances were checked by means of a dial indicator and a stone face plate. The specimen preparation is carried out in accordance with ASTM 4543-01 /4/.

The specimens and the water were weighted using a scale for weight measurement. A thermometer was used for the water temperature measurement. The calculated wet density was determined with an uncertainty of $\pm 4 \text{ kg/m}^3$.

3.2 Mechanical testing

The mechanical tests were carried out in a servo controlled testing machine specially designed for rock tests, see Figure 3-1. The system contains of a load frame, a hydraulic pump unit, a controller unit and various sensors. The communication with the controller unit is made by means of special testing software running on a PC that is connected to the controller. The load frame has a high stiffness and a fast responding actuator, cf the ISRM suggested method /1/. Furthermore, the sensors, the controller and the servo valve are fast responding components. The machine is equipped with a pressure vessel in which the specimens are tested under a confinement pressure. A thin rubber membrane is mounted on the specimen in order to seal the specimen from the oil used as the confinement medium, cf Figure 3-2. The axial load is determined using a load cell, which is located inside the pressure vessel and has a maximum capacity of 1.5 MN. The uncertainty of the load measurement is less than 1%.

The axial and circumferential (radial) deformation of the rock specimen was measured. The rock deformation measurement systems are based on miniature LVDTs, which has a measurement range of $\pm 2.5 \text{ mm}$. The LVDTs were calibrated by means of a micrometer and they displayed an accuracy of $\pm 2.5\%$ within a $\pm 2 \text{ mm}$ range that was used in the tests. The axial deformation measurement system comprises two aluminium rings that are attached on the specimen placed approximately at $\frac{1}{4}$ and $\frac{3}{4}$ of the specimen height, cf Figures 3-2 and 4-1. Two LVDTs mounted on the rings are used to measure the distance change between the rings on opposite side of the specimen. The rings have three adjustable spring-loaded screws each with a rounded tip pointing towards the specimen with 120 degrees division. The rings are mounted directly on the rubber membrane. The pre-load of the screws fixates the rings. The position of the frame piston was also stored during the test in order to give a possibility for comparison with the measurements made with the measurement system that was based on the rings displacement.

The radial deformation was obtained by using a chain mounted around the specimen at mid-height, see Figure 3-2. The change of the chain-opening gap was measured by means of one LVDT and the circumferential and thereby also the radial deformation could be obtained. See Appendix A.

The specimens were photographed with a 4.0 Mega pixel digital camera at highest resolution and the photographs were stored in a jpeg-format.

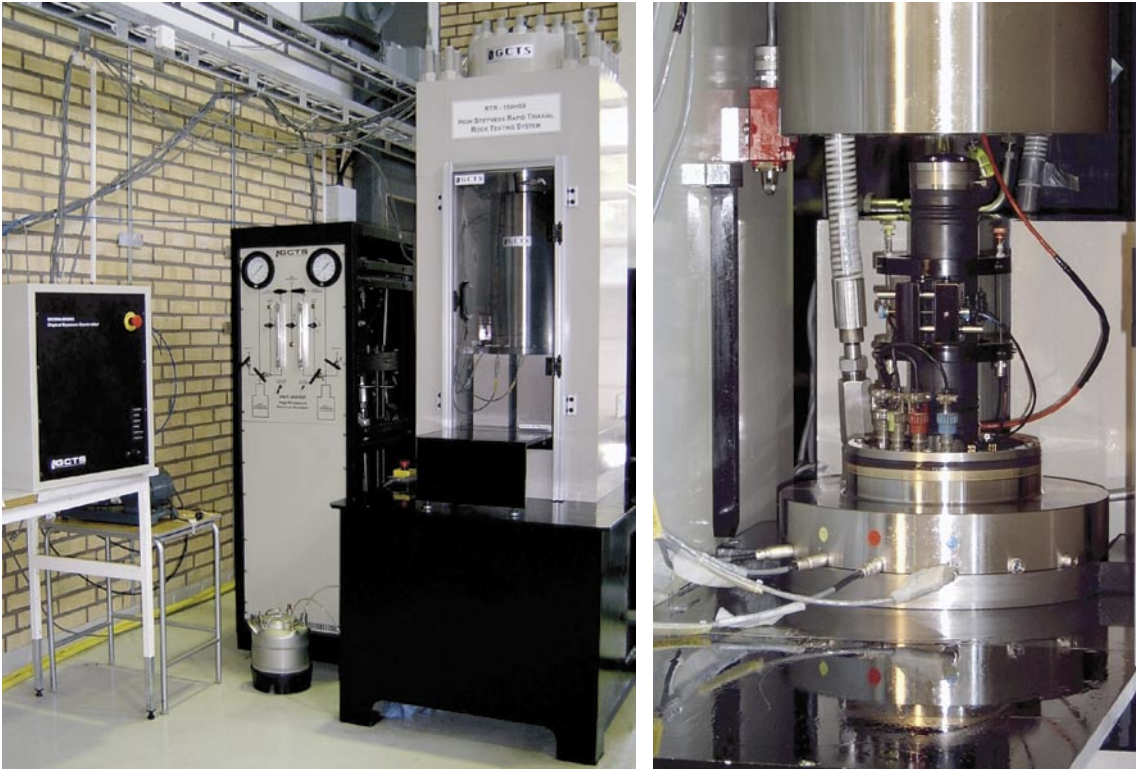


Figure 3-1. Left: Digital controller unit, pressure cabinet with cell pressure intensifier and oil reservoir inside, load frame with closed cell (pressure vessel). Right: Bottom of the cell is lowered. The specimen is instrumented and ready for inserting in the cell.

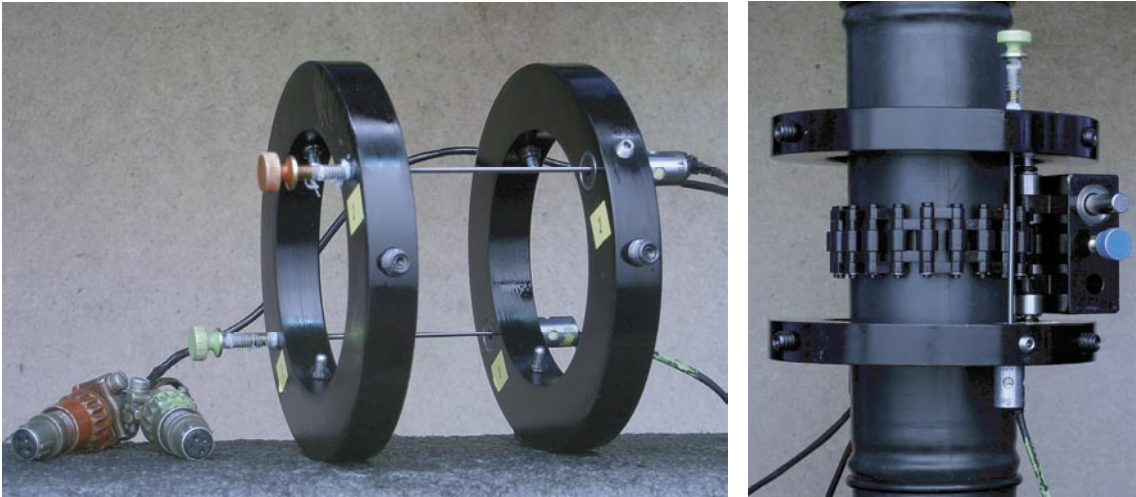


Figure 3-2. Left: Rings and LVDTs for axial deformation measurement. Right: Specimen and loading platens sealed with a rubber membrane. Devices for axial and circumferential deformation measurements are attached.

4 Execution

The water saturation and determination of the density of the wet specimens were made in accordance with the method description SKB MD 160.002, version 2.0, (SKB internal controlling document). This includes determination of density in accordance to ISRM /5/ and water saturation by SS EN 13755 /6/. The triaxial compression tests were carried out according to the method description SKB MD 190.003, version 2.0, (SKB internal controlling document). The test method is based on the ISRM suggested methods /1/ and /7/.

4.1 Description of the specimens

The rock type characterisation was made according to Strähle /8/ using the SKB mapping (Boremap). The identification marks, upper and lower sampling depth (Secup and Seclow) and the rock type are shown in Table 4-1.

Table 4-1. Specimen identification, sampling depth, confining pressure at the triaxial tests and rock type for all specimens.

Identification	Secup (m)	Seclow (m)	Confining pressure (MPa)	Rock type
KLX04A-115-1	307.24	307.38	2	Ävrö granite
KLX04A-115-2	307.38	307.54	7	Ävrö granite
KLX04A-115-3	307.54	307.68	7	Ävrö granite
KLX04A-115-4	307.79	307.93	10	Ävrö granite
KLX04A-115-5	308.52	308.66	10	Ävrö granite
KLX04A-115-7	565.37	565.51	2	Ävrö granite
KLX04A-115-8	565.51	565.65	7	Ävrö granite
KLX04A-115-9	565.65	565.79	7	Ävrö granite
KLX04A-115-10	565.79	565.93	15	Ävrö granite
KLX04A-115-12	750.65	750.79	2	Ävrö granite
KLX04A-115-13	750.79	750.93	7	Ävrö granite
KLX04A-115-14	751.09	751.23	7	Ävrö granite
KLX04A-115-15	751.23	751.37	20	Ävrö granite
KLX04A-115-16	751.37	751.51	20	Ävrö granite

4.2 Specimen preparation and density measurement

The temperature of the water was 18.5°C, which equals to a water density of 998.5 kg/m³, when the determination of the wet density of the rock specimens was carried out. Further, the specimens had been stored 20 days in water when the density was determined.

A step-by step description of the procedure for the specimen preparation and the density measurement is as follows:

Step	Activity
1	The drill cores were marked where the specimens are to be taken.
2	The specimens were cut to the specified length according to markings and the cutting surfaces were grinded.
3	The tolerances were checked: parallel and perpendicular end surfaces, smooth and straight circumferential surface.
4	The diameter and height were measured three times each. The respectively mean value determines the dimensions that are reported.
5	The specimens were then water saturated according to the method described in SKB MD 160.002, version 2.0, (SKB internal controlling document) and were stored for minimum 7 days in water whereupon the wet density was determined.

4.3 Mechanical testing

The specimens had been stored 55–61 days in water when the triaxial compression tests were carried out. The functionality of the triaxial testing system was checked, by carrying out tests on other cores with a similar type rock before the tests described in this report started. A check-list was filled in successively during the work in order to confirm that the different specified steps have been carried out. Moreover, comments were made upon observed things during the mechanical testing that are relevant for the interpretation of the results. The check-list form is a SP internal quality document.

A step-by step description of the test procedure is as follows:

Step	Activity
1	Digital photos were taken on each specimen before the mechanical testing.
2	The specimen was put in testing position and centred between the loading platens.
3	A rubber membrane was mounted on the specimen and the devices for measuring axial and circumferential deformations were attached to the specimen on top of the rubber membrane.
4	The core on each LVDT was adjusted by means of a set screw to the right initial position. This was done so that the optimal range of the LVDTs can be used for the deformation measurement.
5	The triaxial cell was closed and filled with oil whereby a cell pressure of 0.6 MPa is applied.
6	The frame piston was brought down into contact with the specimen with a force corresponding to a deviatoric stress of 0.6 MPa. The cell pressure was then raised to the specified level and at the same time keeping the deviatoric stress constant.
7	The deformation measurement channels were zeroed in the test software.
8	The loading was started and the initial loading rate was set to a radial strain rate of –0.025%/min. The loading rate was increased after reaching the post-failure region. This was done in order to prevent the total time for the test to become too long.
9	The test was stopped either manually when the test had proceeded large enough to see the post-failure behaviour, or after severe cracking had occurred and it was judged that very little residual axial loading capacity was left in the specimen.
10	The oil pressure was brought down to zero and the oil was poured out of the cell. The cell was opened and the specimen taken out.
11	Digital photos were taken on each specimen after the mechanical testing.

4.4 Data handling

The test results were exported as text files from the test software and stored in a file server on the SP computer network after each completed test. The main data processing, in which the elastic moduli were computed and the peak stress was determined, has been carried out in the program MATLAB /9/. Moreover, MATLAB was used to produce the diagrams shown in Section 5.1 and in Appendix B. The summary of results in Section 5.2 with tables containing mean value and standard deviation of the different parameters and diagrams were produced using MS Excel. MS Excel was also used for reporting data to the SICADA database.

4.5 Analyses and interpretation

As to the definition of the different results parameters we begin with the axial stress σ_a , which is defined as

$$\sigma_a = \frac{F}{A}$$

where F is the axial force acting on the specimen and A is specimen cross section area. The pressure vessel (triaxial cell) filled with oil specimen is pressurized with a cell (confining) pressure p . This implies that the specimen becomes confined and the radial stress σ_r of the specimen is equal to confining pressure p . The (effective) deviatoric stress is defined as

$$\sigma_{\text{dev}} = \sigma_a - \sigma_r$$

The peak value of the axial stress during a test is representing the triaxial compressive strength σ_c , for the actual confining pressure used in the test, in the results presentation.

The average value of the two axial displacement measurements on opposite sides of the specimen is used for the axial strain calculation. The recorded deformation δ_{local} represents a local axial displacement between the points approximately at $\frac{1}{4}$ and $\frac{3}{4}$ of the specimen height, cf Figure 4-1. The axial strain is defined as

$$\varepsilon_a = \delta_{\text{local}}/L_{\text{local}}$$

where L_{local} is the distance between the rings before loading.

The radial deformation is measured by means of a chain mounted around the specimen at mid-height, see Figure 3-2. The change of chain opening gap is measured by means of one LVDT. This measurement is used to compute the radial strain ε_r , see Appendix A. Moreover, the volumetric strain ε_{vol} is defined as

$$\varepsilon_{\text{vol}} = \varepsilon_a + 2\varepsilon_r$$

The stresses and the strains are defined as positive in compressive loading and deformation. The elasticity parameters are defined by the tangent Young's modulus E and tangent Poisson ratio ν as

$$E = \frac{\sigma_a(0.55 \sigma_c) - \sigma_a(0.45 \sigma_c)}{\varepsilon_a(0.55 \sigma_c) - \varepsilon_a(0.45 \sigma_c)}$$

$$\nu = -\frac{\varepsilon_r(0.55 \sigma_c) - \varepsilon_r(0.45 \sigma_c)}{\varepsilon_a(0.55 \sigma_c) - \varepsilon_a(0.45 \sigma_c)}$$

The tangents were evaluated with values corresponding to an axial load between 45% and 55% of the axial peak stress σ_c .

A closure of present micro cracks will take place initially during confinement and axial loading. Development of new micro cracks will start when the axial load is further increased and axial stress reaches the crack initiation stress σ_i . The crack growth at this stage is as stable as increased loading is required for further cracking. A transition from a development of micro cracks to macro cracks will take place when the axial load is further increased. At a certain stress level the crack growth becomes unstable. The stress level when this happens is denoted the crack damage stress σ_d , cf /2, 3/. In order to determine the stress levels we look at the volumetric strain.

By subtracting the elastic volumetric strain ϵ_{vol}^e from the total volumetric strain a volumetric strain corresponding to the crack volume is obtained ϵ_{vol}^{cr} . This has been denoted calculated crack volumetric strain in the literature, cf /2, 3/. We have thus

$$\epsilon_{vol}^{cr} = \epsilon_{vol} - \epsilon_{vol}^e$$

Assuming linear elasticity leads to

$$\epsilon_{vol}^{cr} = \epsilon_{vol} - \frac{1-2\nu}{E}(\sigma_a - \sigma_r)$$

Experimental investigations have shown that the crack initiation stress σ_i coincides with the onset of increase of the calculated crack volume, cf /2, 3/. The same investigations also indicate that the crack damage stress σ_d can be defined as the axial stress at which the total volume starts to increase, i.e. when a dilatant behaviour is observed.

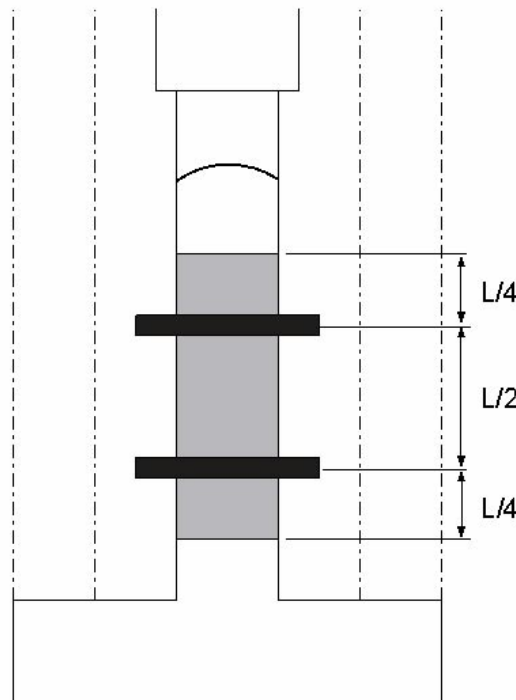


Figure 4-1. Sketch showing the triaxial cell with the rock specimen (grey) with height L and the placement of the rings (black) used for the axial deformation measurements. The membrane is omitted in the figure for simplicity.

5 Results

The results of the individual specimens are presented in Section 5.1 and a summary of the results is given in Section 5.2. The reported parameters are based on unprocessed raw data obtained from the testing and were reported to the SICADA database, FN 428. These data together with the digital photographs of the individual specimens were stored on a CD and handed over to SKB. The handling of the results follows SDP-508 (SKB internal controlling document) in general.

5.1 Description and presentation of the specimen

The cracking is shown in pictures taken on the specimens with comments on observed things that appeared during the testing. The elasticity parameters have been evaluated by using the results from the local deformation measurements. Red rings are superposed on the graphs indicating every five minutes of the progress of testing. The results for the individual specimens are as follows:

Specimen ID: KLX04A-115-1

Before mechanical test

After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.8	2,650
Comments	Multiple spalling around the specimen.	

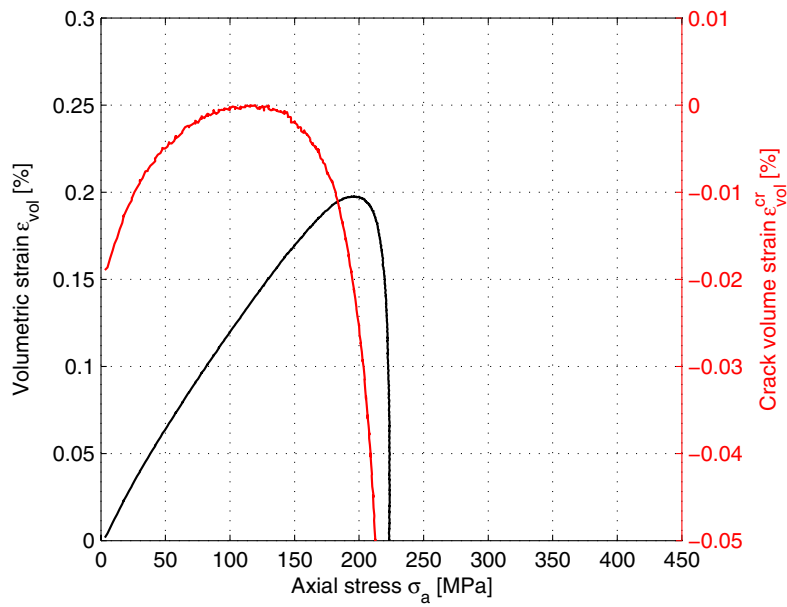
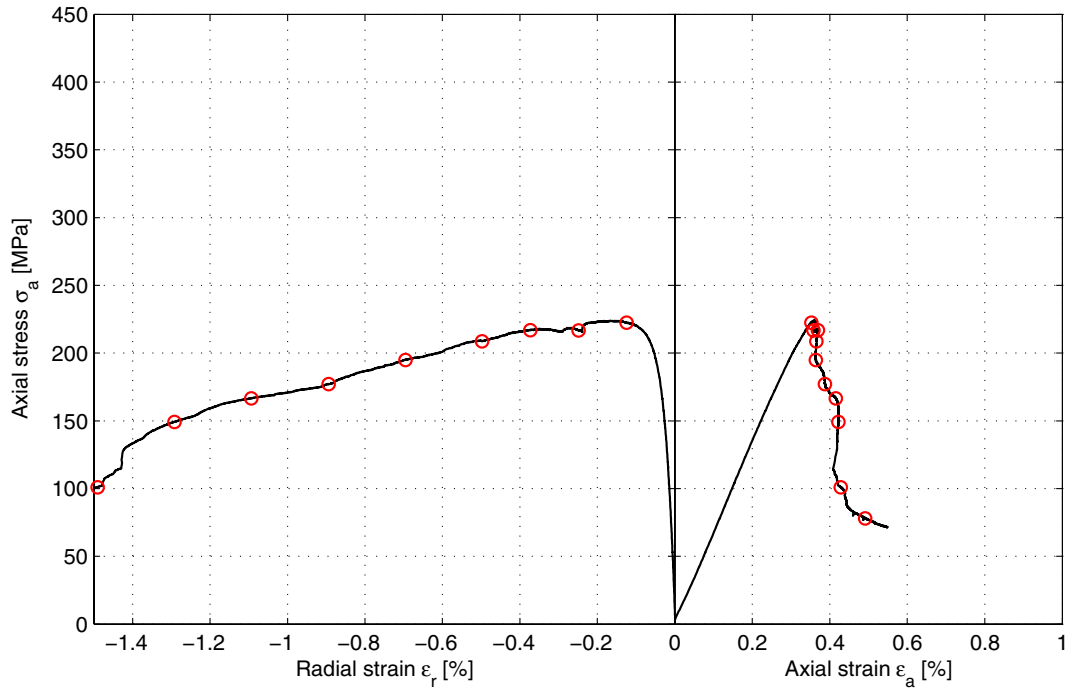
Specimen ID: KLX04A-115-01

Youngs Modulus (E): 68.3 [GPa]

Cell pressure: 2 [MPa]

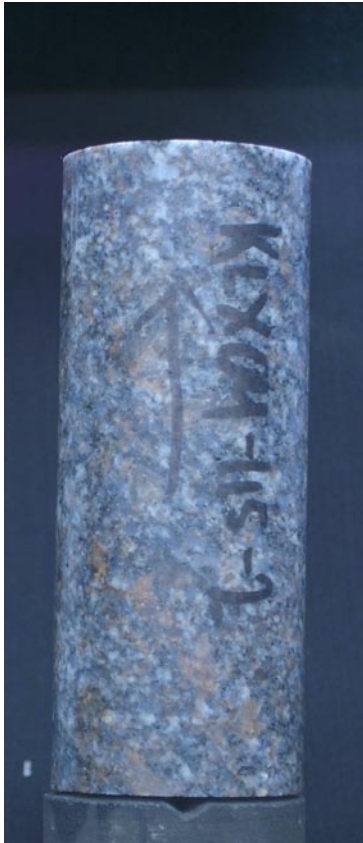
Poisson Ratio (ν): 0.15 [-]

Axial peak stress (σ_c): 223.9 [MPa]



Specimen ID: KLX04A-115-2

Before mechanical test



After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.8	2,670
Comments	Two steep v-formed shear cracks are observed.	

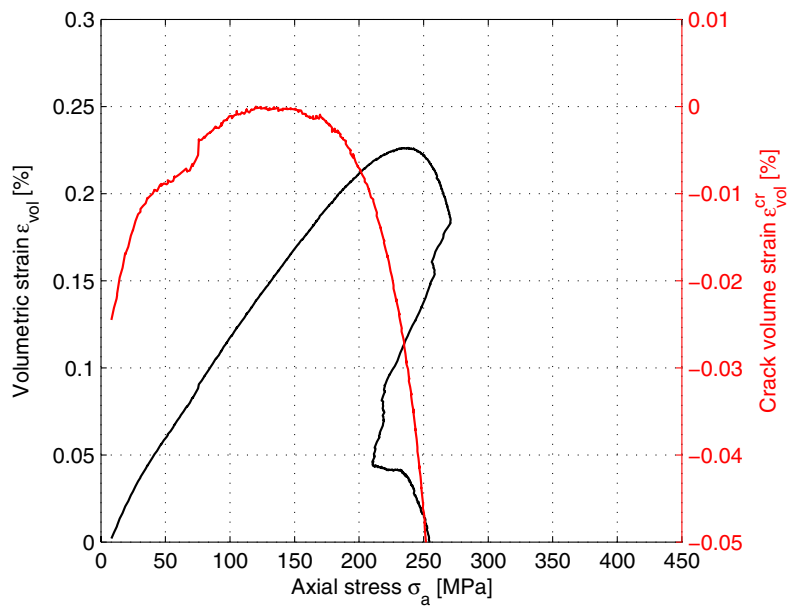
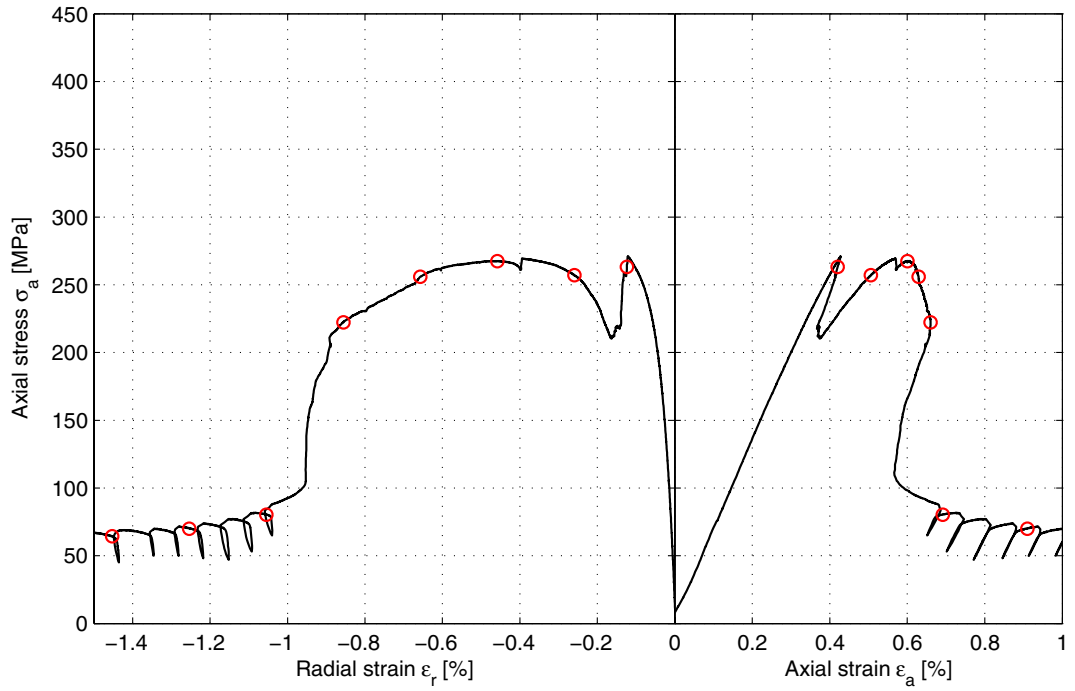
Specimen ID: KLX04A-115-02

Youngs Modulus (E): 67 [GPa]

Cell pressure: 7 [MPa]

Poisson Ratio (ν): 0.165 [-]

Axial peak stress (σ_c): 271 [MPa]



Specimen ID: KLX04A-115-3

Before mechanical test

After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.4	126.8	2,670
Comments	One major shear crack has been formed.	

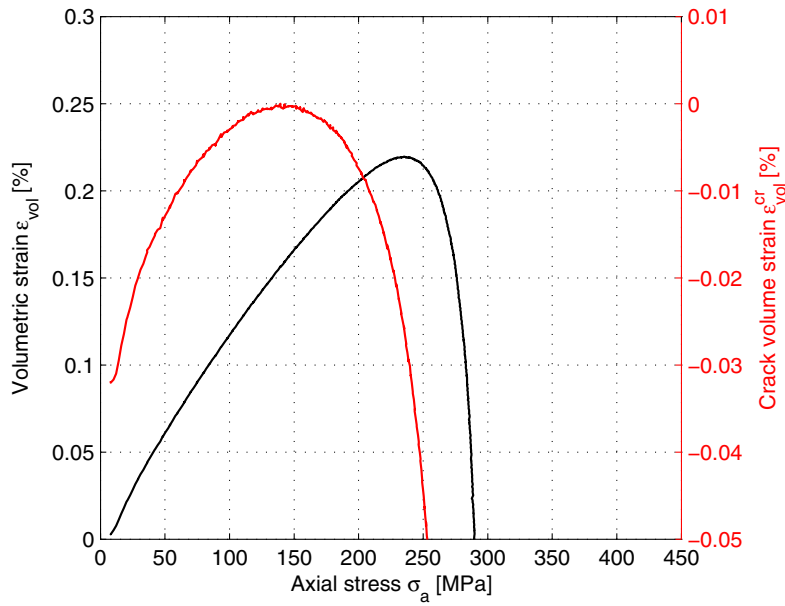
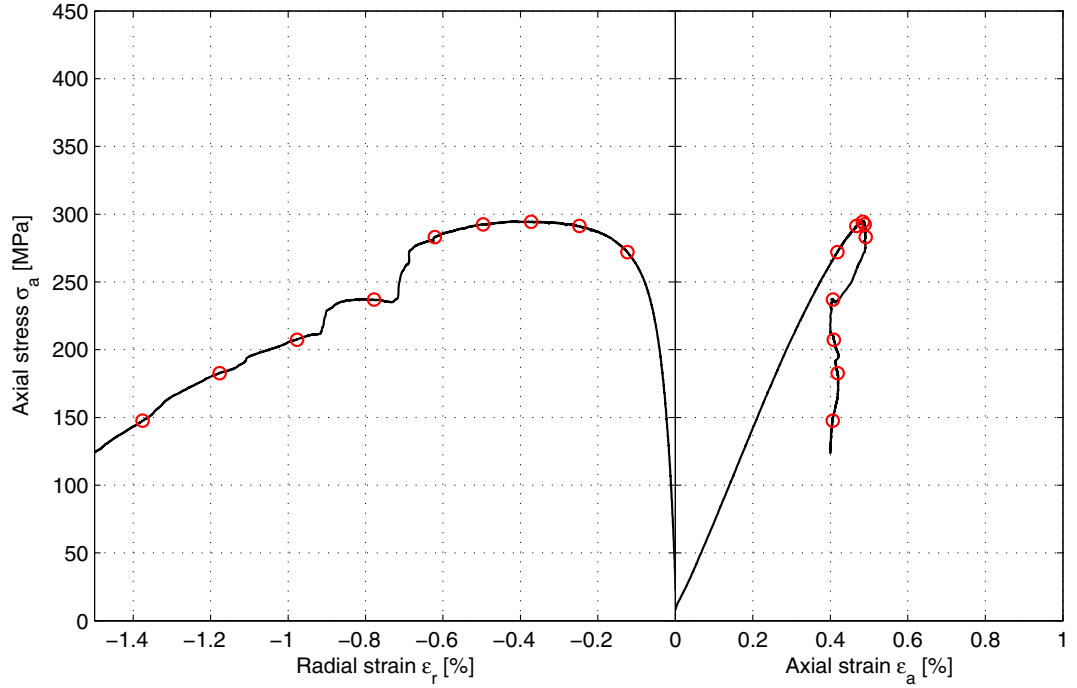
Specimen ID: KLX04A-115-03

Youngs Modulus (E): 68.7 [GPa]

Cell pressure: 7 [MPa]

Poisson Ratio (ν): 0.182 [-]

Axial peak stress (σ_c): 294.7 [MPa]



Specimen ID: KLX04A-115-4

Before mechanical test

After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.8	2,670

Comments Two less steep v-formed shear cracks are observed.

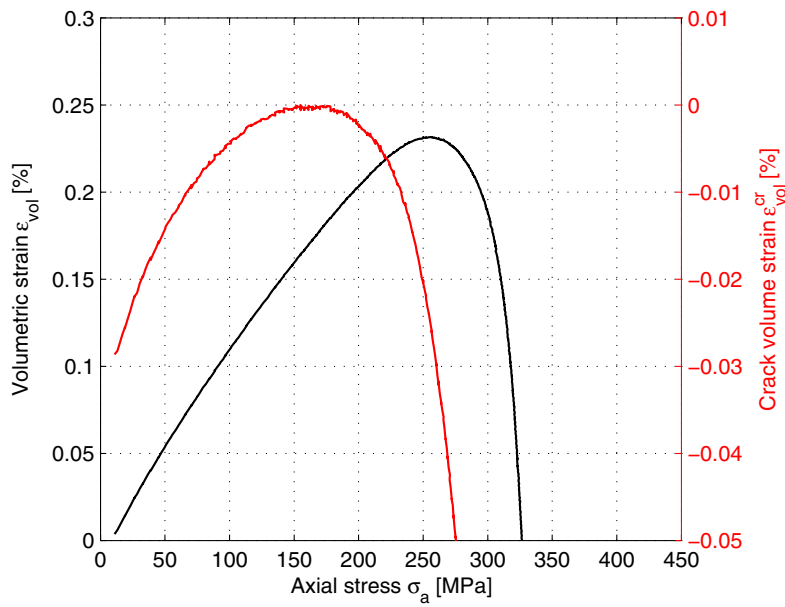
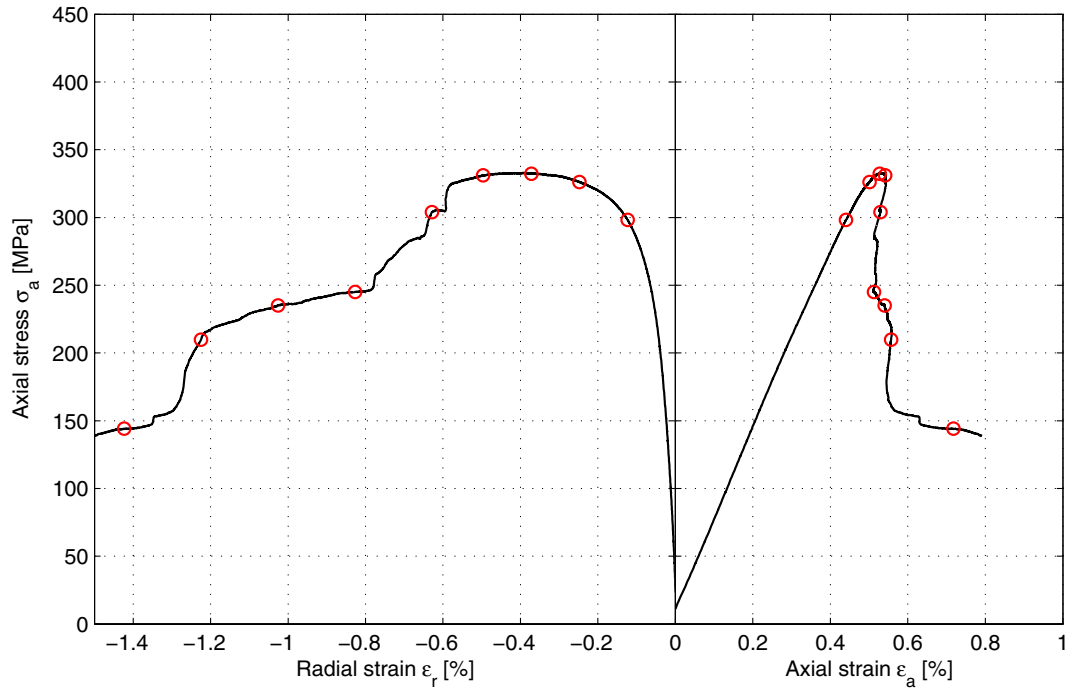
Specimen ID: KLX04A-115-04

Youngs Modulus (E): 67.8 [GPa]

Cell pressure: 10 [MPa]

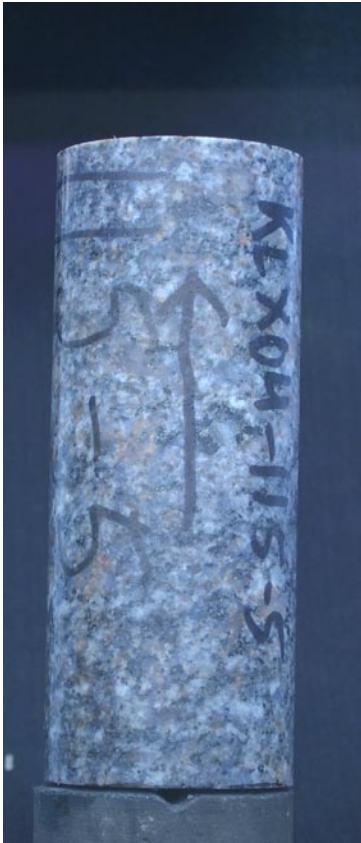
Poisson Ratio (ν): 0.189 [-]

Axial peak stress (σ_c): 332.9 [MPa]



Specimen ID: KLX04A-115-5

Before mechanical test



After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.9	2,690
Comments	Two less steep v-formed shear cracks are observed.	

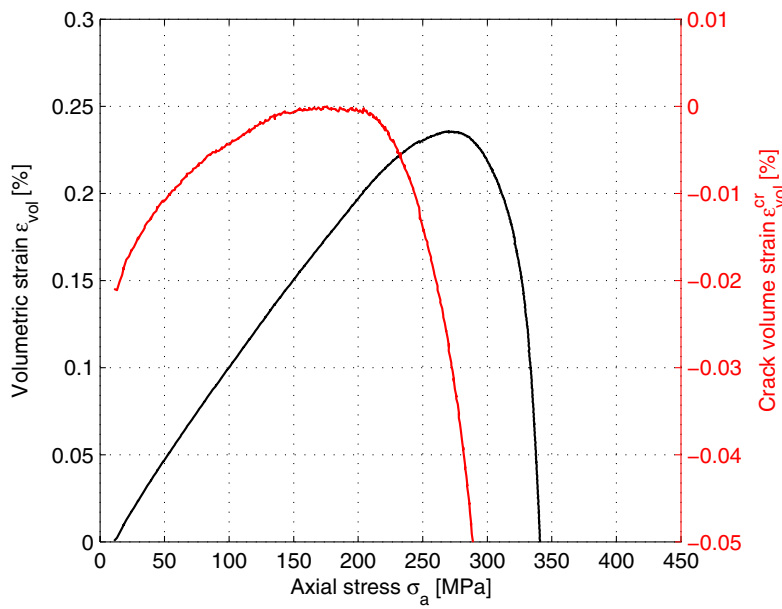
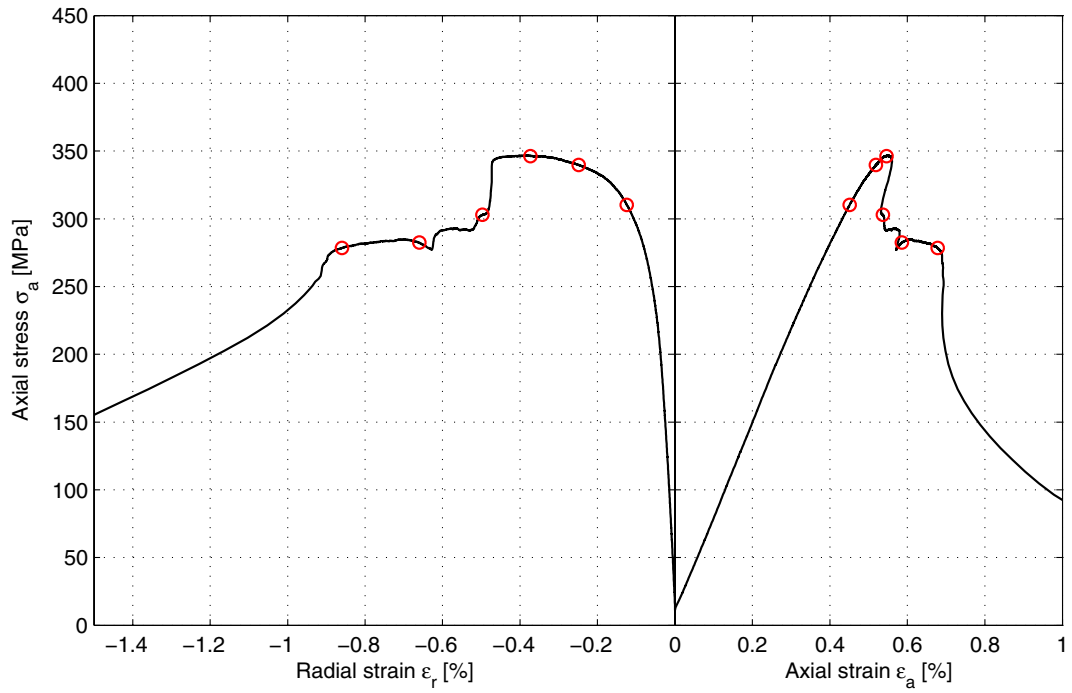
Specimen ID: KLX04A-115-05

Youngs Modulus (E): 71.1 [GPa]

Cell pressure: 10 [MPa]

Poisson Ratio (ν): 0.169 [-]

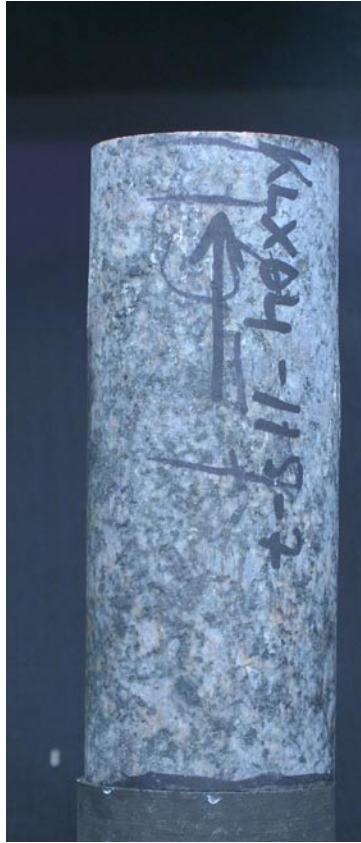
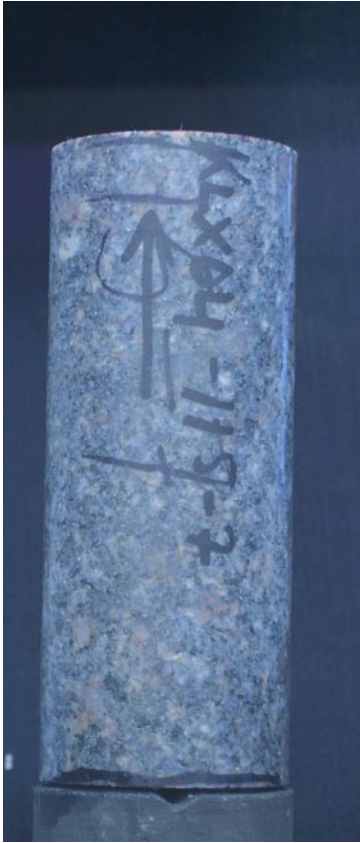
Axial peak stress (σ_c): 346.8 [MPa]



Specimen ID: KLX04A-115-7

Before mechanical test

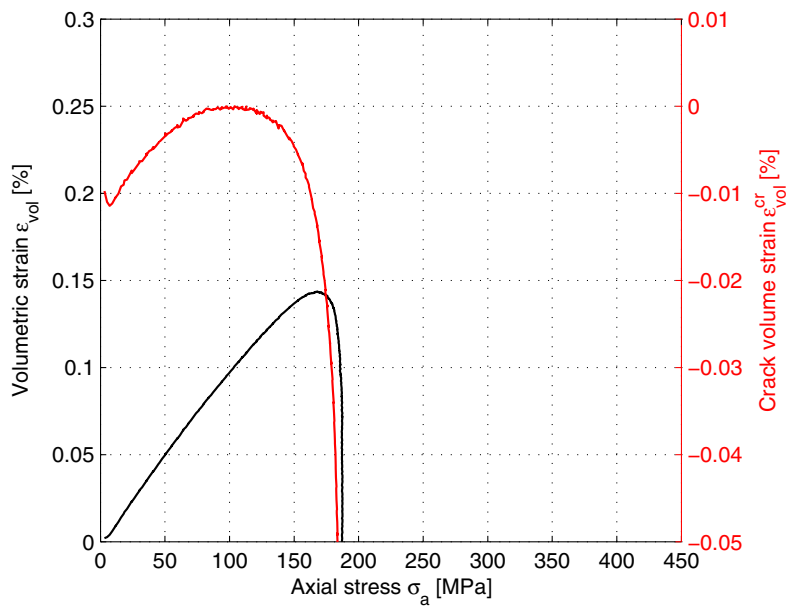
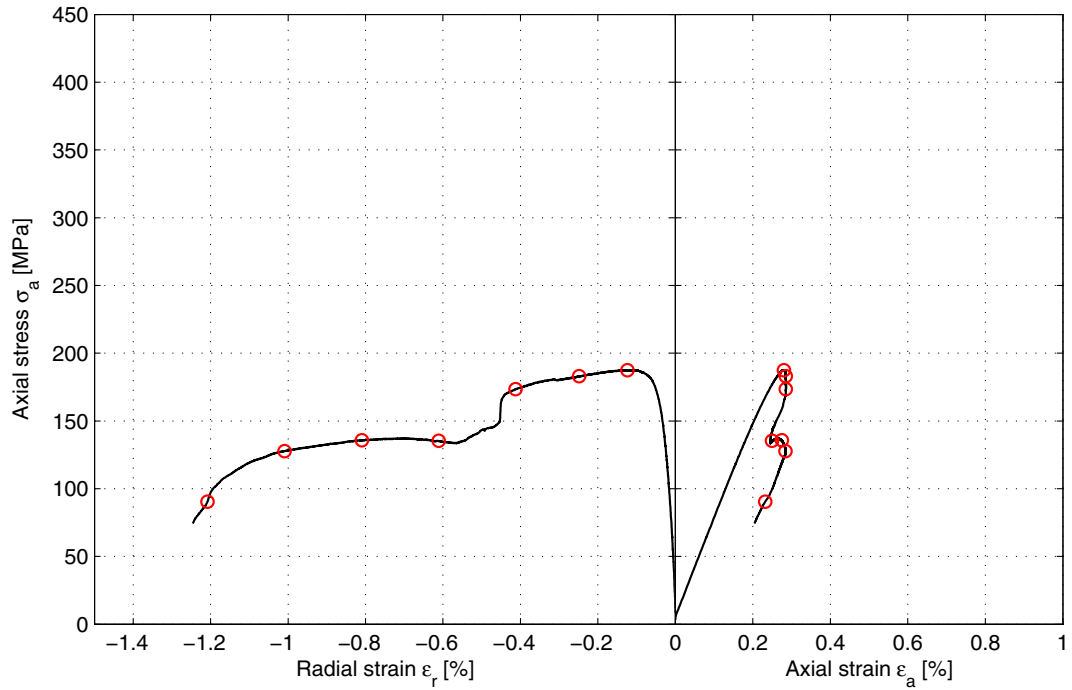
After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.2	127.5	2,740
Comments	Steep shear cracks are observed.	

Specimen ID: KLX04A-115-07

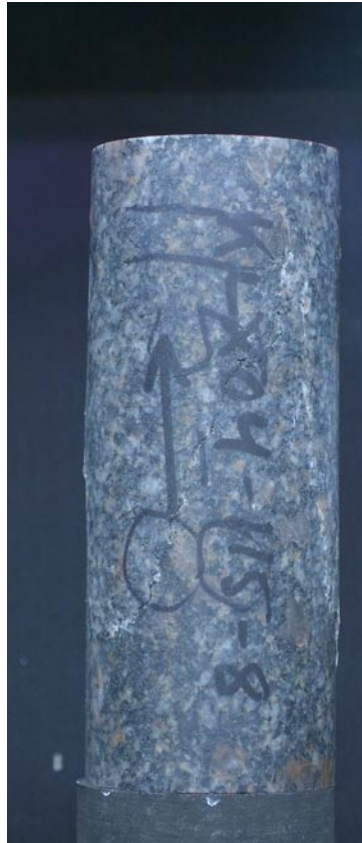
Youngs Modulus (E): 72.6 [GPa] Cell pressure: 2 [MPa]
Poisson Ratio (ν): 0.18 [-]
Axial peak stress (σ_c): 187.5 [MPa]



Specimen ID: KLX04A-115-8

Before mechanical test

After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.2	127.6	2,740

Comments Two steep v-formed shear cracks are observed.

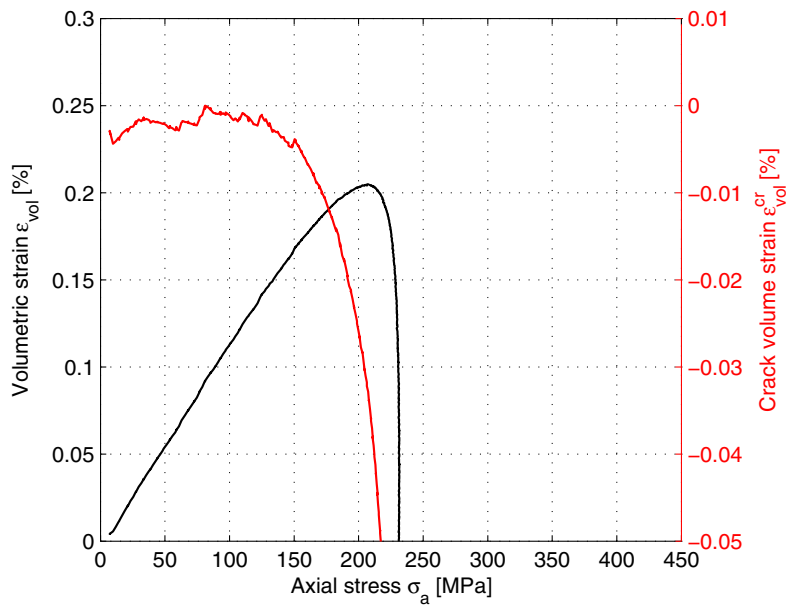
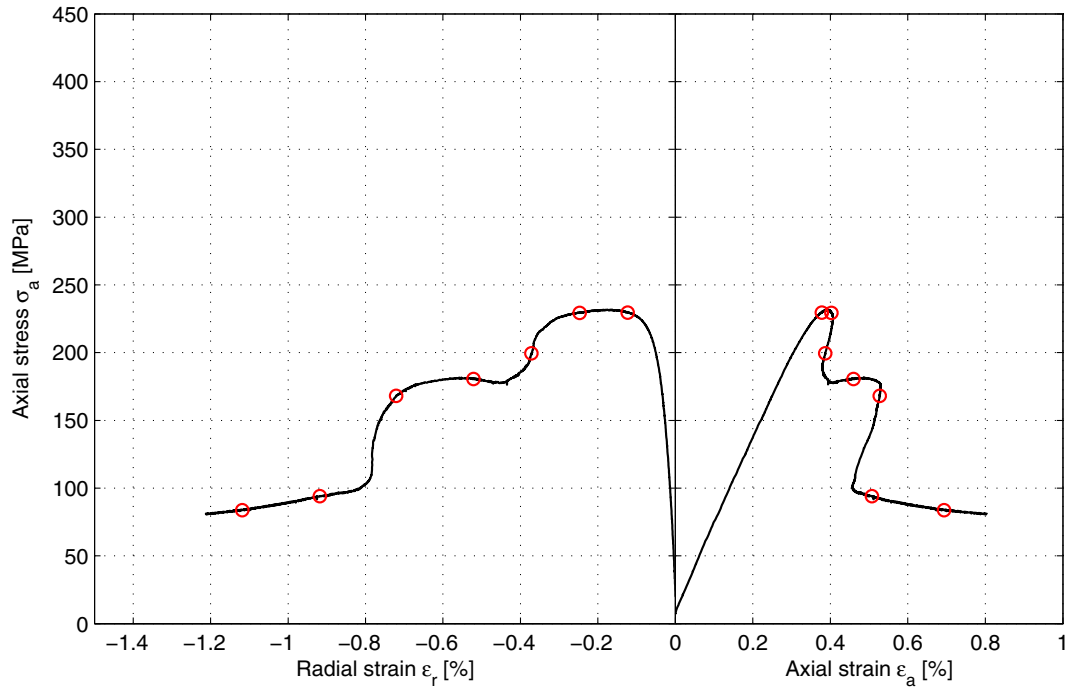
Specimen ID: KLX04A-115-08

Youngs Modulus (E): 60.8 [GPa]

Cell pressure: 7 [MPa]

Poisson Ratio (ν): 0.15 [-]

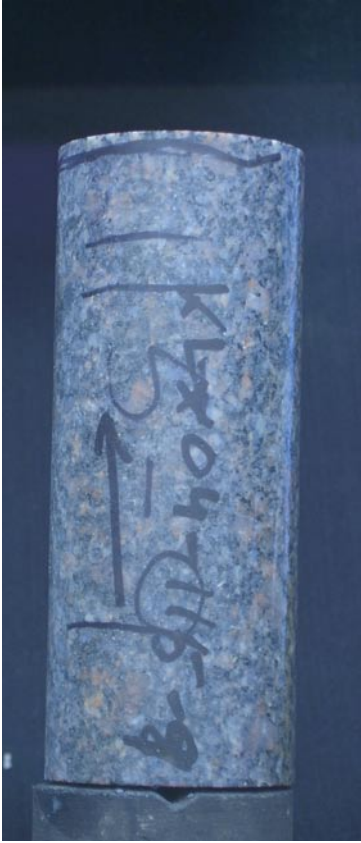
Axial peak stress (σ_c): 231.7 [MPa]



Specimen ID: KLX04A-115-9

Before mechanical test

After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.2	127.6	2,730
Comments	One major shear crack has been formed.	

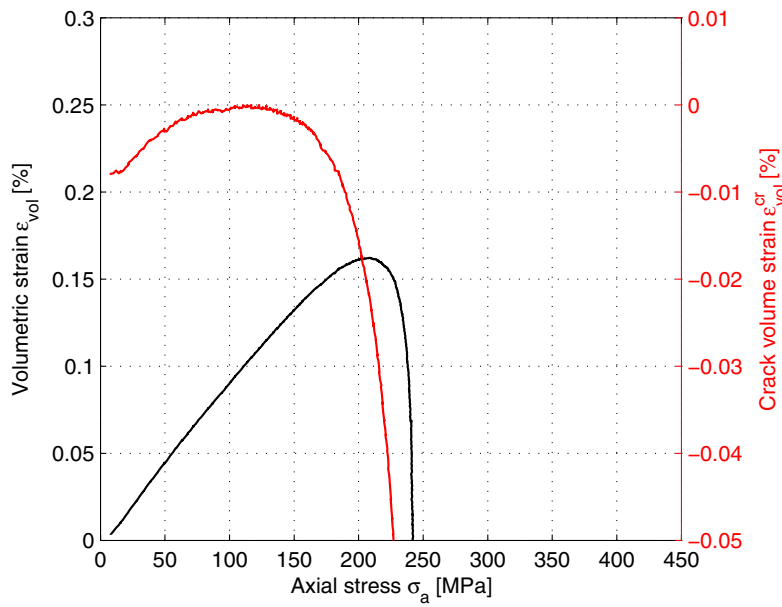
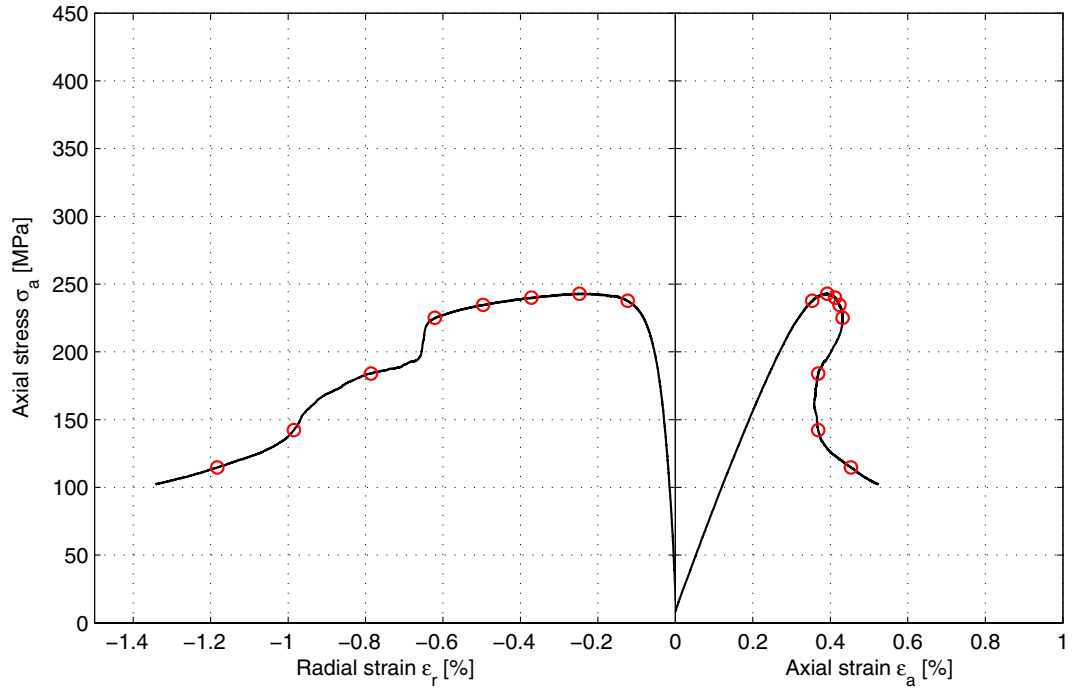
Specimen ID: KLX04A-115-09

Youngs Modulus (E): 70.7 [GPa]

Cell pressure: 7 [MPa]

Poisson Ratio (ν): 0.195 [-]

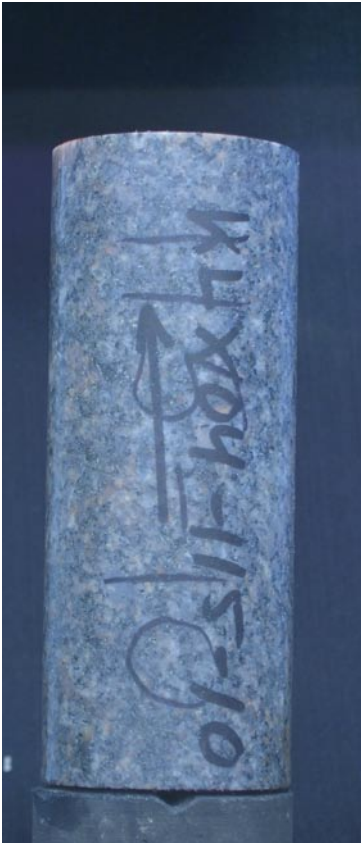
Axial peak stress (σ_c): 243 [MPa]



Specimen ID: KLX04A-115-10

Before mechanical test

After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.2	127.6	2,730
Comments	One major shear crack has been formed.	

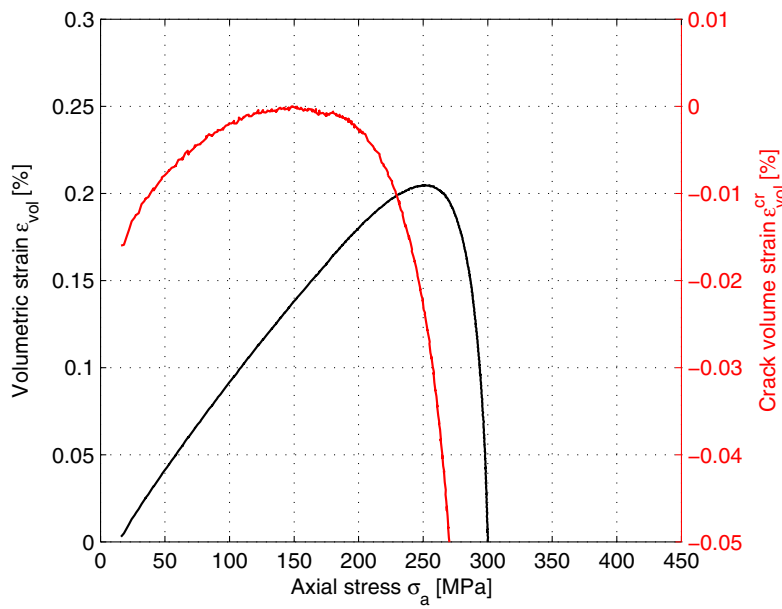
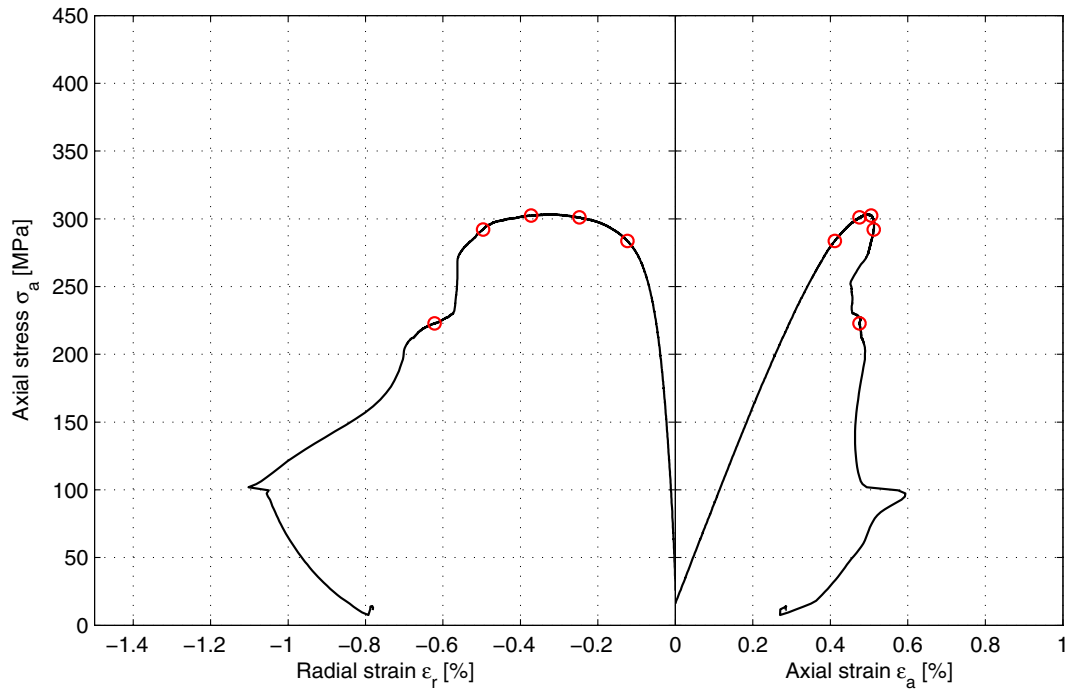
Specimen ID: KLX04A-115-10

Youngs Modulus (E): 70.3 [GPa]

Cell pressure: 15 [MPa]

Poisson Ratio (ν): 0.187 [-]

Axial peak stress (σ_c): 303.3 [MPa]



Specimen ID: KLX04A-115-12

Before mechanical test

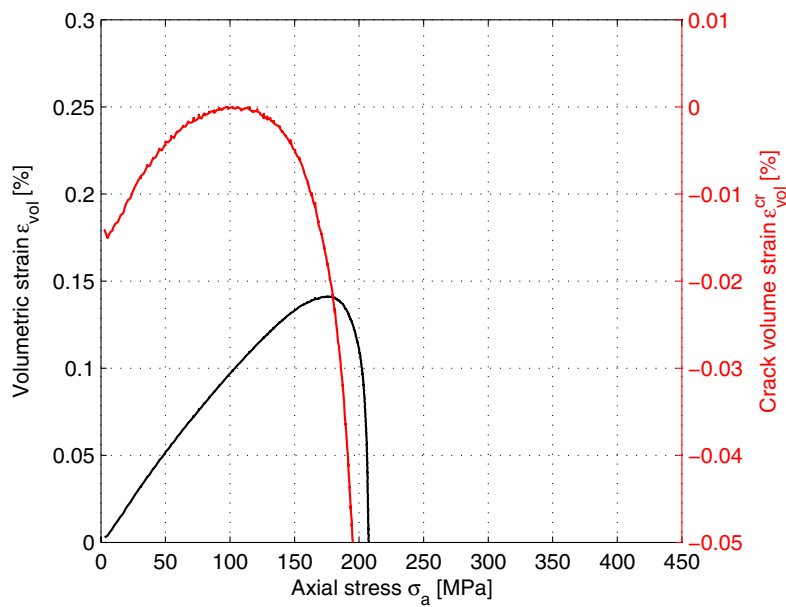
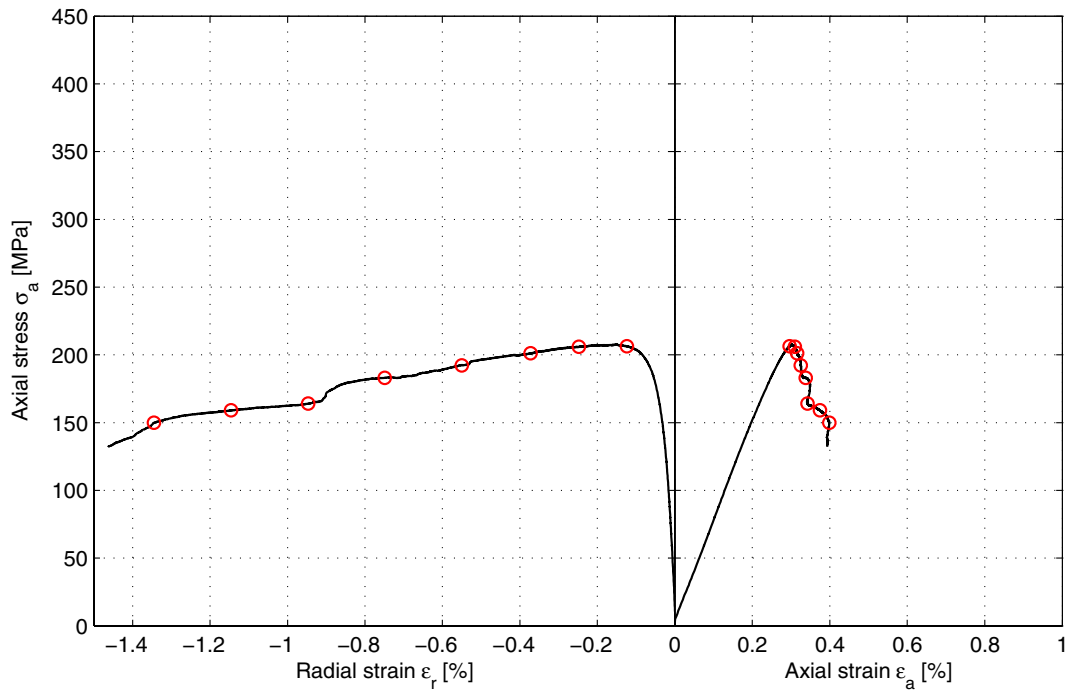
After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.9	2,700
Comments	Spalling mainly on one side of the specimen.	

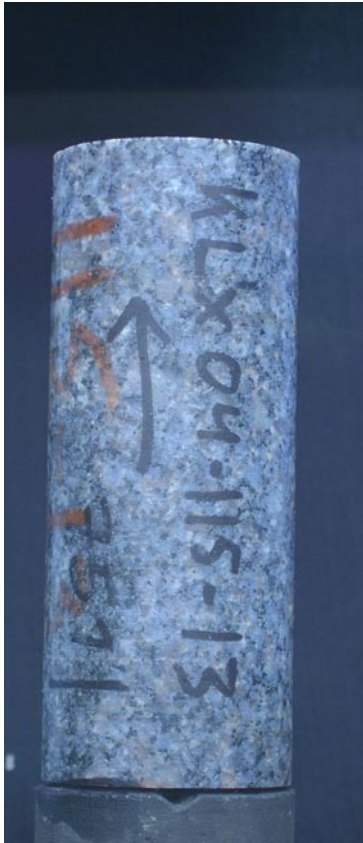
Specimen ID: KLX04A-115-12

Youngs Modulus (E): 75.9 [GPa] Cell pressure: 2 [MPa]
Poisson Ratio (ν): 0.188 [-]
Axial peak stress (σ_c): 207.6 [MPa]



Specimen ID: KLX04A-115-13

Before mechanical test



After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.9	2,720

Comments Two major less steep v-formed shear cracks are observed. In addition, a membrane leakage is also observed. The specimen has been quite much damaged due to excessive axial deformation after completed test when the piston accidentally was moved in the wrong direction.

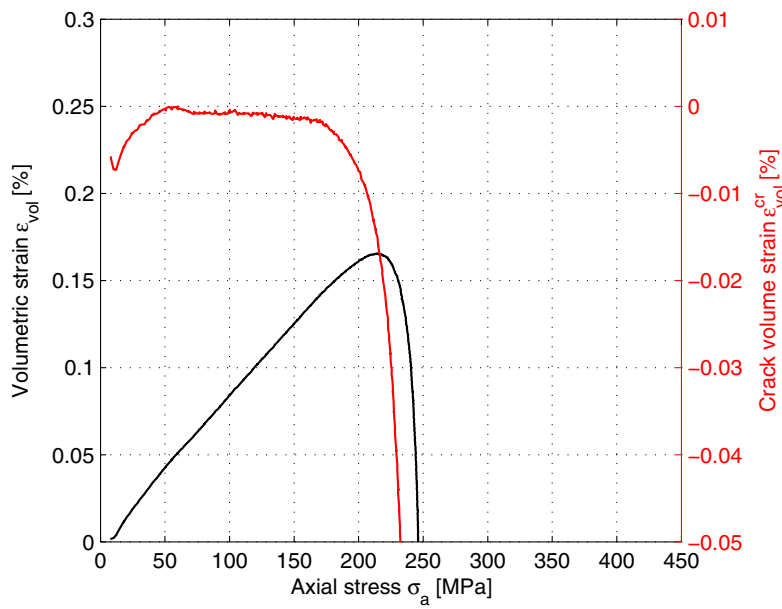
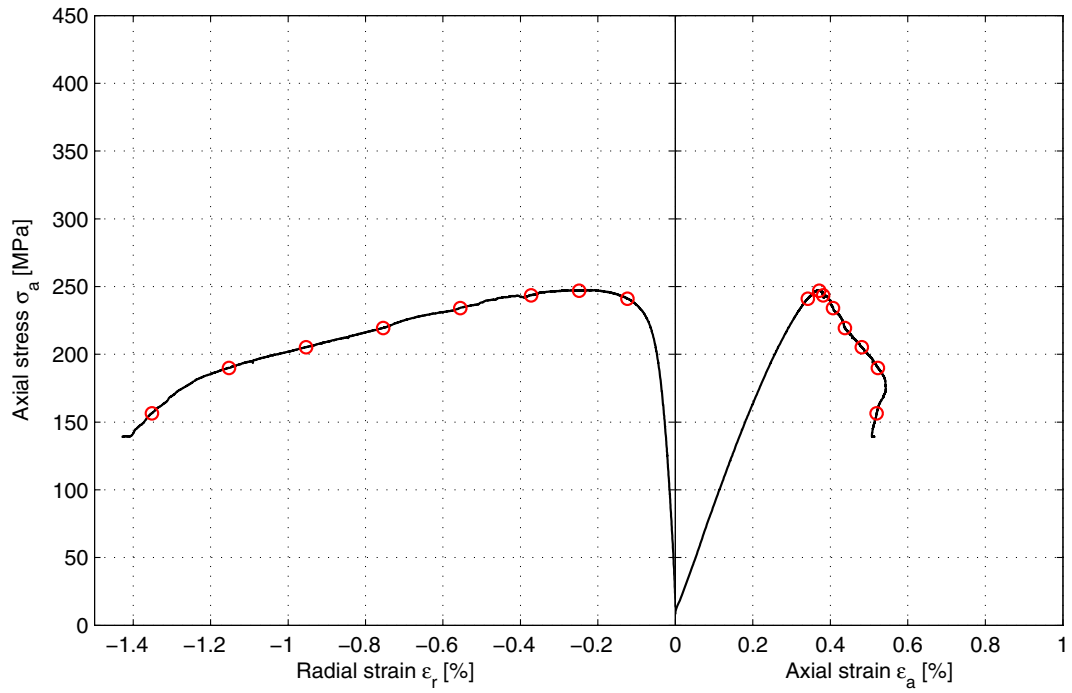
Specimen ID: KLX04A-115-13

Youngs Modulus (E): 76.2 [GPa]

Cell pressure: 7 [MPa]

Poisson Ratio (ν): 0.181 [-]

Axial peak stress (σ_c): 247.4 [MPa]



Specimen ID: KLX04A-115-14

Before mechanical test

After mechanical test



Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.8	2,740
Comments	Two step v-formed shear cracks are observed.	

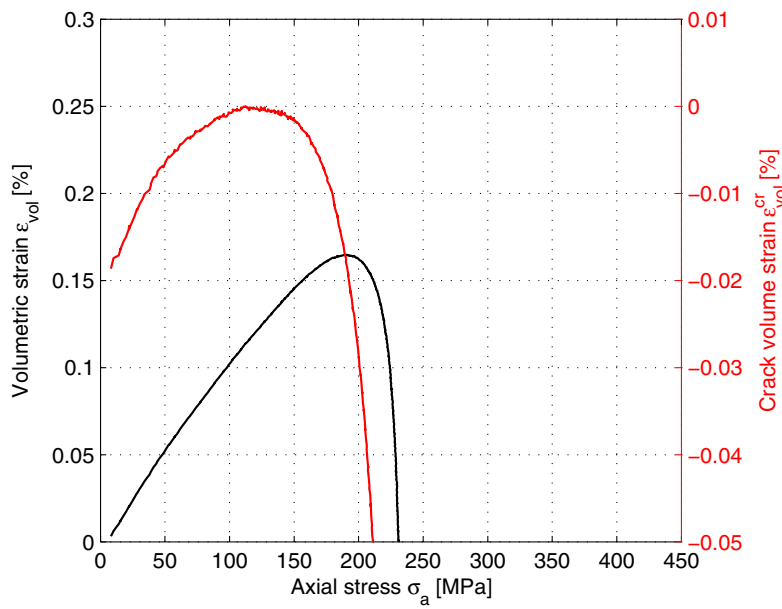
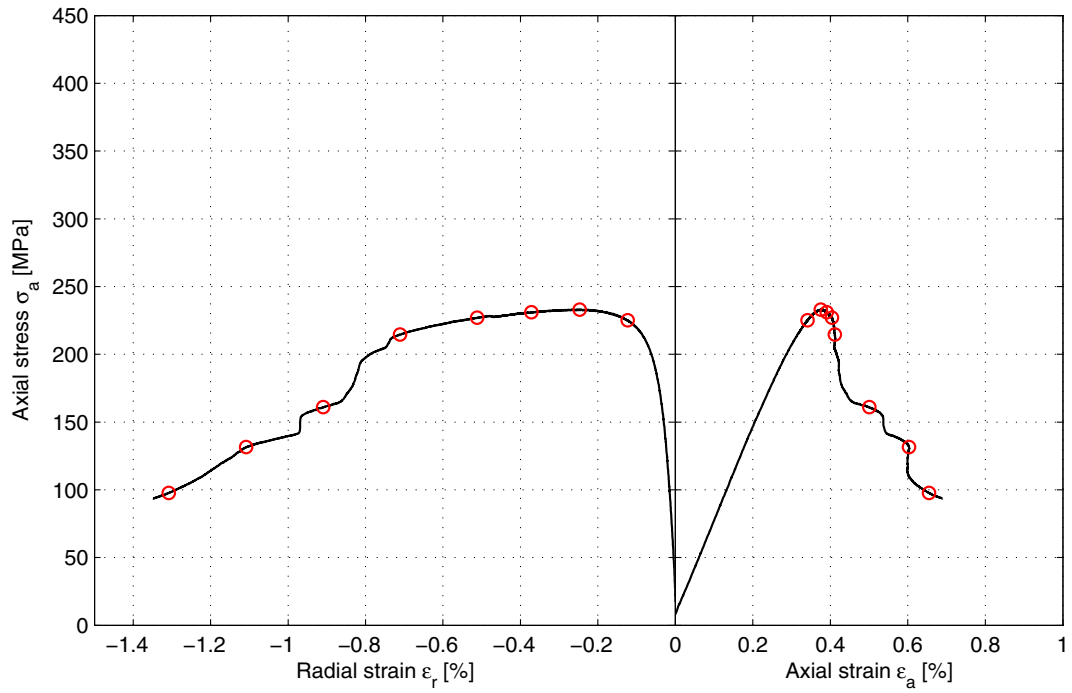
Specimen ID: KLX04A-115-14

Youngs Modulus (E): 70.3 [GPa]

Cell pressure: 7 [MPa]

Poisson Ratio (ν): 0.19 [-]

Axial peak stress (σ_c): 233 [MPa]



Specimen ID: KLX04A-115-15

Before mechanical test

After mechanical test

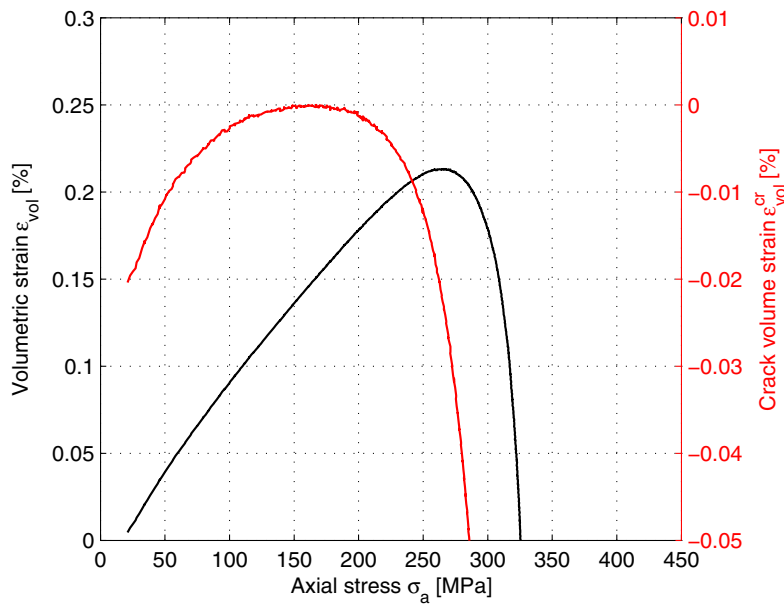
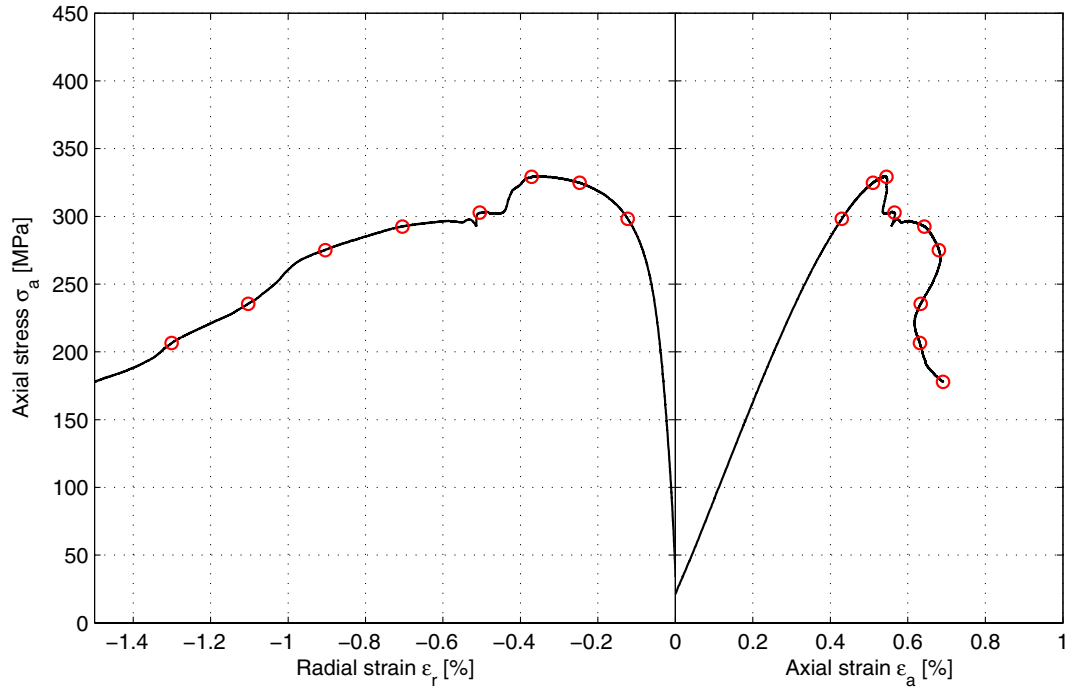


Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.8	2,740

Comments Two less steep v-formed shear cracks are observed. In addition, a small membrane leakage is also observed.

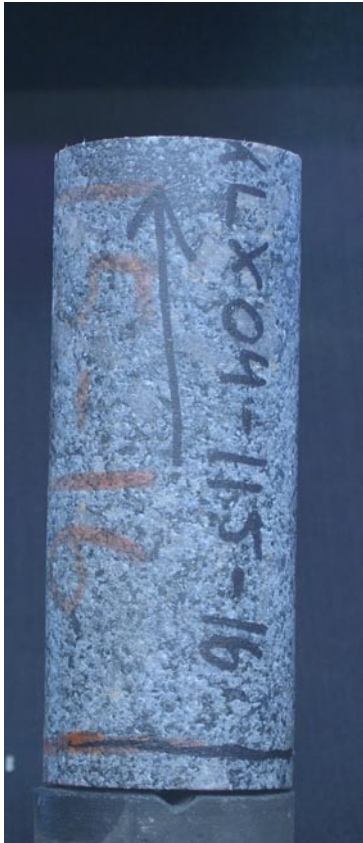
Specimen ID: KLX04A-115-15

Youngs Modulus (E): 70.1 [GPa] Cell pressure: 20 [MPa]
Poisson Ratio (ν): 0.198 [-]
Axial peak stress (σ_c): 329.7 [MPa]



Specimen ID: KLX04A-115-16

Before mechanical test



After mechanical test

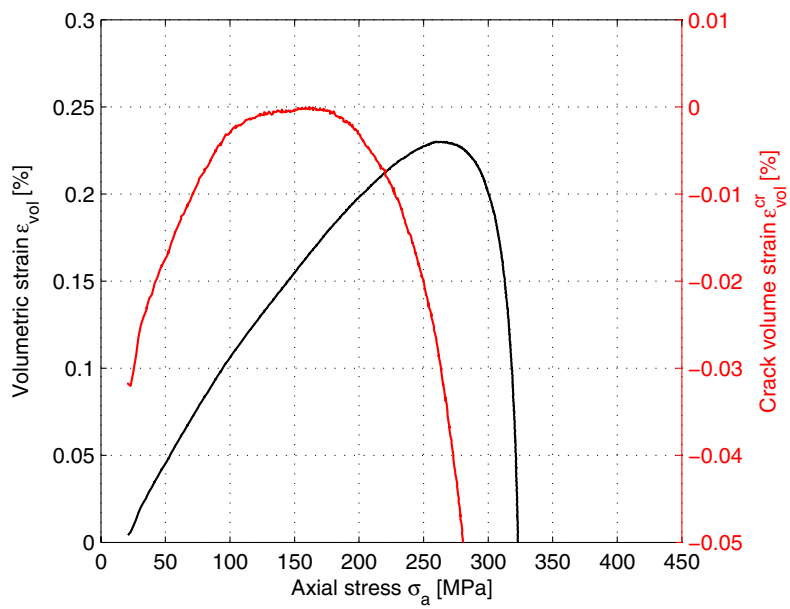
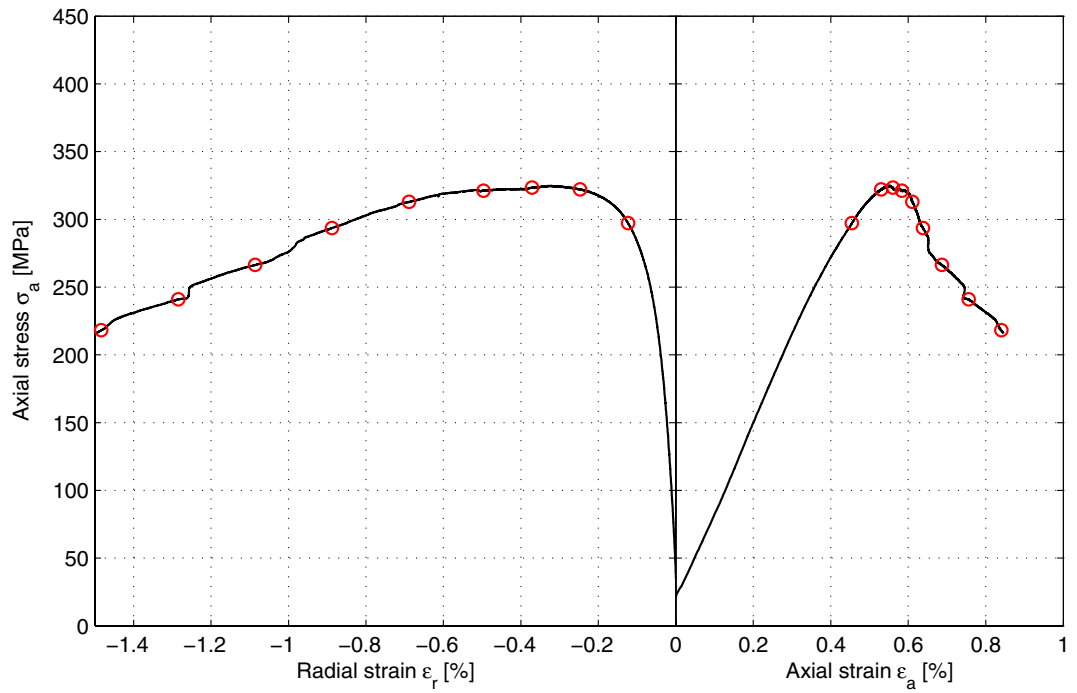


Diameter (mm)	Height (mm)	Density (kg/m³)
50.3	126.8	2,740

Comments One primary major shear crack followed by a secondary shear crack seems to have been formed. A small membrane leakage is observed.

Specimen ID: KLX04A-115-16

Youngs Modulus (E): 66.5 [GPa] Cell pressure: 20 [MPa]
Poisson Ratio (ν): 0.193 [-]
Axial peak stress (σ_c): 324.7 [MPa]



5.2 Results for the entire test series

A summary of the test results is shown in Tables 5-1 and 5-2. The densities, triaxial compressive strength, the tangent Young's modulus and the tangent Poisson ratio versus the depth, at which the specimens are taken, are shown in Figures 5-1 to 5-4.

Table 5-1. Summary of results.

Identification	Conf press (MPa)	Density (kg/m ³)	Compressive strength (MPa)	Young's modulus (GPa)	Poisson ratio (-)	Comments
KLX04A-115-1	2	2,650	223.9	68.3	0.15	
KLX04A-115-2	7	2,670	271.0	67.0	0.16	
KLX04A-115-3	7	2,670	294.7	68.7	0.18	
KLX04A-115-4	10	2,670	332.9	67.8	0.19	
KLX04A-115-5	10	2,690	346.8	71.1	0.17	
KLX04A-115-7	2	2,740	187.5	72.6	0.18	
KLX04A-115-8	7	2,740	231.7	60.8	0.15	
KLX04A-115-9	7	2,730	243.0	70.7	0.20	
KLX04A-115-10	15	2,730	303.3	70.3	0.19	
KLX04A-115-12	2	2,700	207.6	75.9	0.19	
KLX04A-115-13	7	2,720	247.4	76.2	0.18	
KLX04A-115-14	7	2,740	233.0	70.3	0.19	
KLX04A-115-15	20	2,740	329.7	70.1	0.20	
KLX04A-115-16	20	2,740	324.7	66.5	0.19	

Table 5-2. Calculated mean values and standard deviation.

	Density (kg/m ³)	Young's modulus (GPa)	Poisson ratio (-)
Mean value	2,709	69.7	0.18
Standard deviation	33.2	3.9	0.02

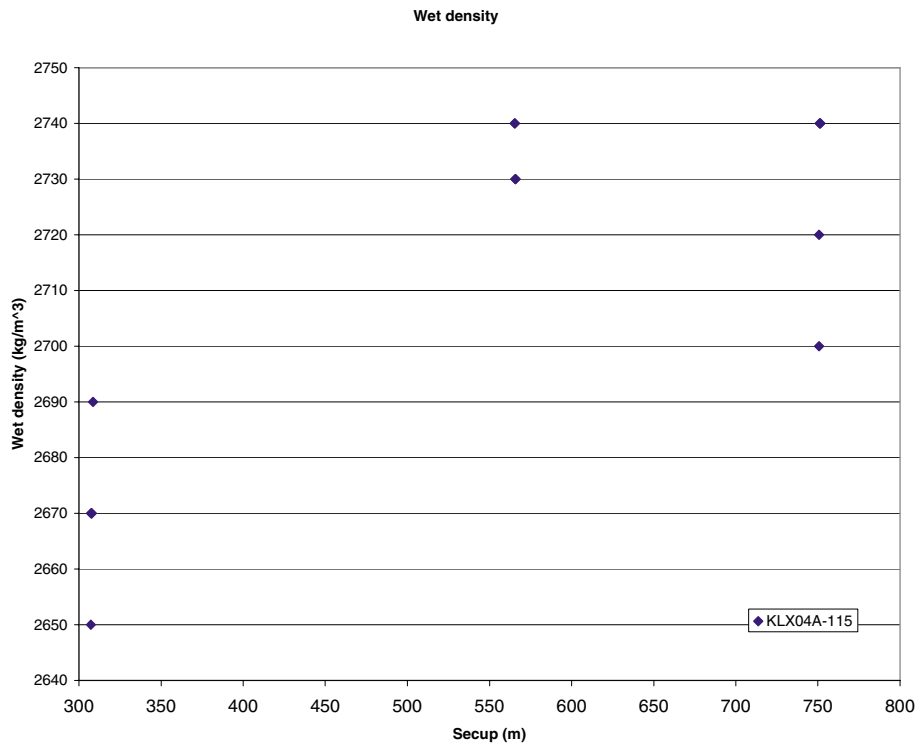


Figure 5-1. Density versus depth at which the specimens are taken in the borehole.

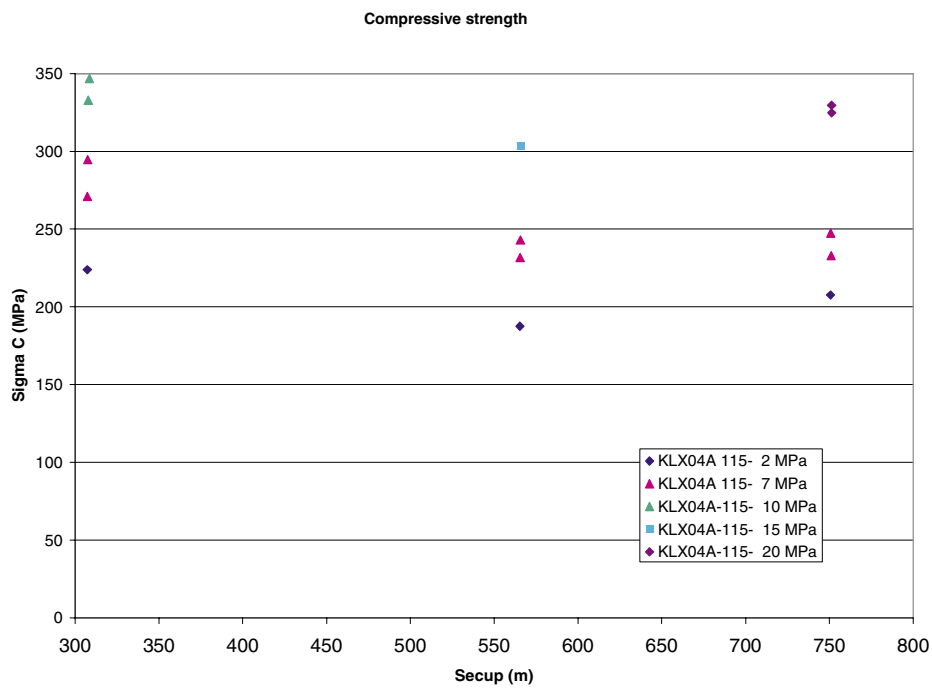


Figure 5-2. Compressive strength versus depth at which the specimens are taken in the borehole.

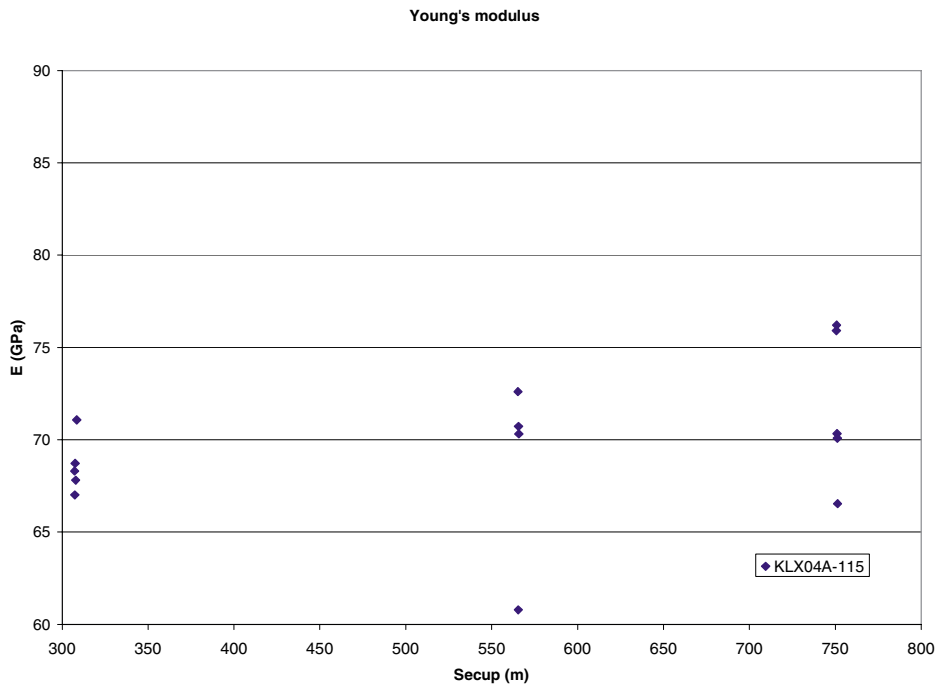


Figure 5-3. Tangent Young's modulus versus depth at which the specimens are taken in the borehole.

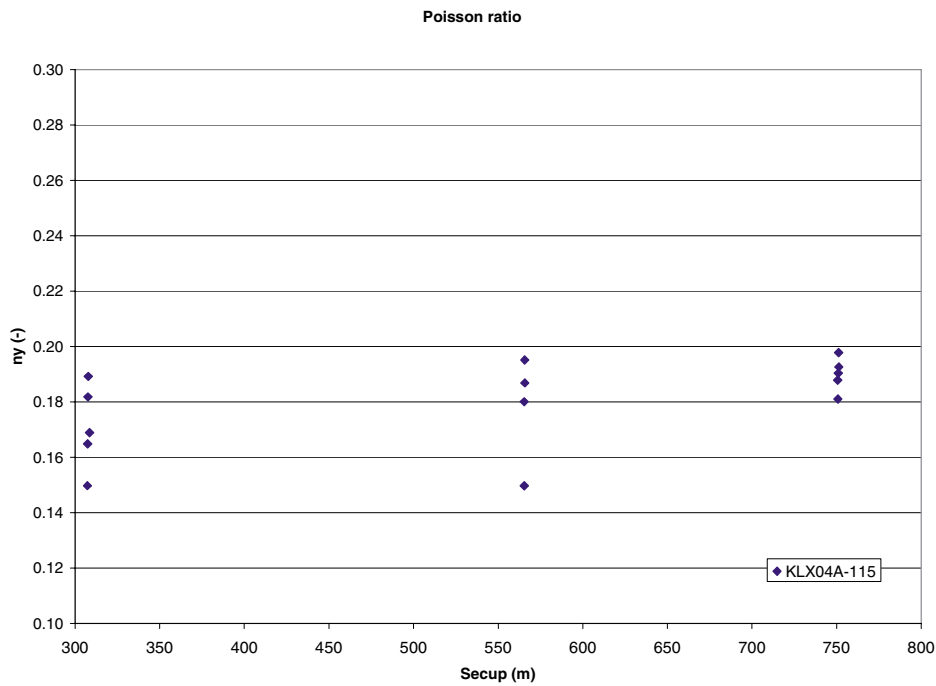


Figure 5-4. Tangent Poisson ratio versus depth at which the specimens are taken in the borehole.

5.3 Discussion

The testing was conducted according to the method description except for one deviation. The circumferential strains have been determined within a relative error of 1.5%, which is larger than what is specified in the ISRM-standard /1/. One specimen (KLX04A-115-13) was accidentally damaged after the test was completed and the specimen was going to be taken out from the cell. The piston was manually controlled in order to raise it to its upper position. By mistake it was lowered some millimeters and the specimen became damaged.

The activity plan was followed with no departures.

References

- /1/ **ISRM, 1999.** Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression, *Int. J. Rock. Mech. Min. Sci.* 36(3), pp 279–289.
- /2/ **Martin C D, Chandler N A, 1994.** The progressive fracture of Luc du Bonnet granite, *Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr.* 31(6), pp 643–659.
- /3/ **Eberhardt E, Stead D, Stimpson B, Read R S, 1998.** Identifying crack initiation and propagation thresholds in brittle rock. *Can. Geotech. J.* 35, pp 222–233.
- /4/ **ASTM 4543-01, 2001.** Standard practice for preparing rock core specimens and determining dimensional and shape tolerance.
- /5/ **ISRM, 1979.** Suggested Method for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-durability Index Properties, *Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr.* 16(2), pp 141–156.
- /6/ **SS-EN 13755.** Natural stone test methods – Determination of water absorption at atmospheric pressure.
- /7/ **ISRM, 1983.** suggested method for determining the strength of rock material in triaxial compression: Revised version, *Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr.* 20(6), pp 283–290.
- /8/ **Stråhle A, 2001.** Definition och beskrivning av parametrar för geologisk, geofysisk och bergmekanisk kartering av berg. SKB R-01-19, Svensk Kärnbränslehantering AB. In Swedish.
- /9/ **MATLAB, 2002.** The Language of Technical computing. Version 6.5. MathWorks Inc.

Appendix A

The following equations describe the correct calculation of radial strains when using a circumferential deformation device, see Figure A-1.

$$\varepsilon_r = \frac{\Delta C}{C_i}$$

where

$$C_i = 2 \pi R_i = \text{initial specimen circumference}$$

$$\Delta C = \text{change in specimen circumference} = \frac{\pi \cdot \Delta X}{\sin\left(\frac{\theta_i}{2}\right) + \left(\pi - \frac{\theta_i}{2}\right) \cos\left(\frac{\theta_i}{2}\right)}$$

and

$$\Delta X = \text{change in LVDT reading} = X_i - X_f$$

(X_i = initial chain gap; X_f = current chain gap)

$$\theta_i = \text{initial chord angle} = 2 \pi - \frac{L_c}{R_i + r}$$

$$L_c = \text{chain length (measured from center of one end roller to center of other end roller)}$$

r = roller radius

R_i = initial specimen radius

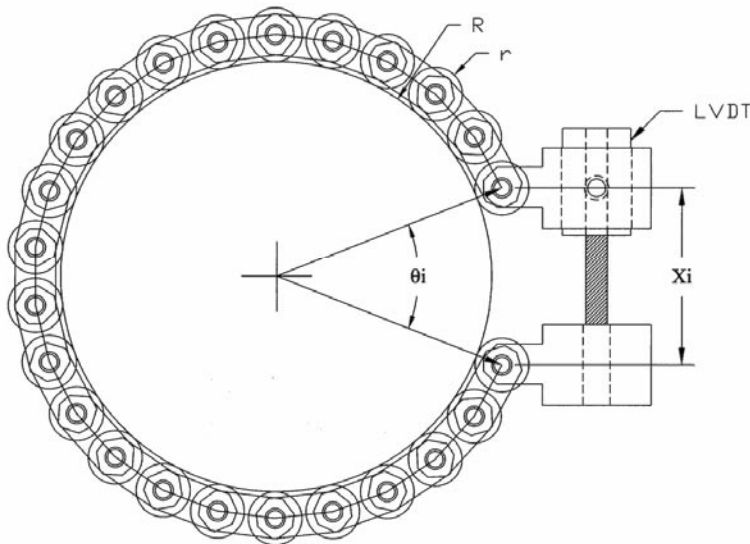
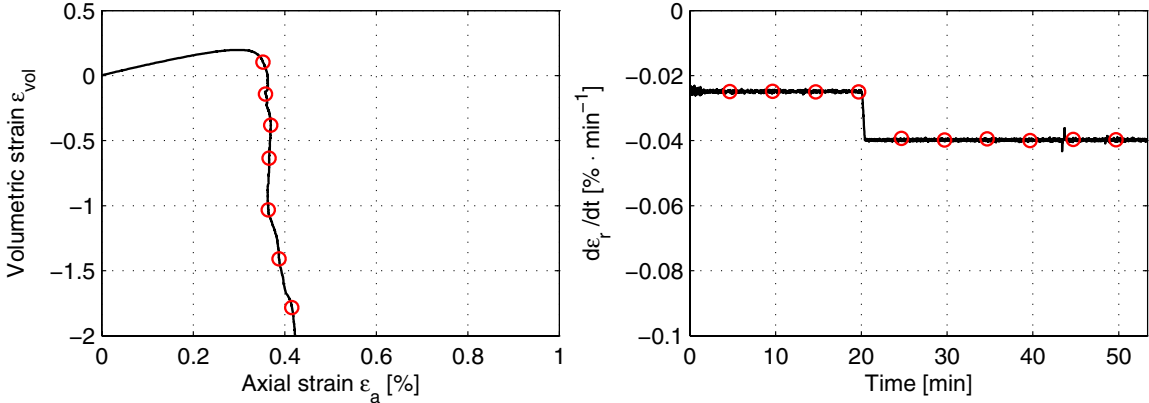


Figure A-1. Chain for radial deformation measurement.

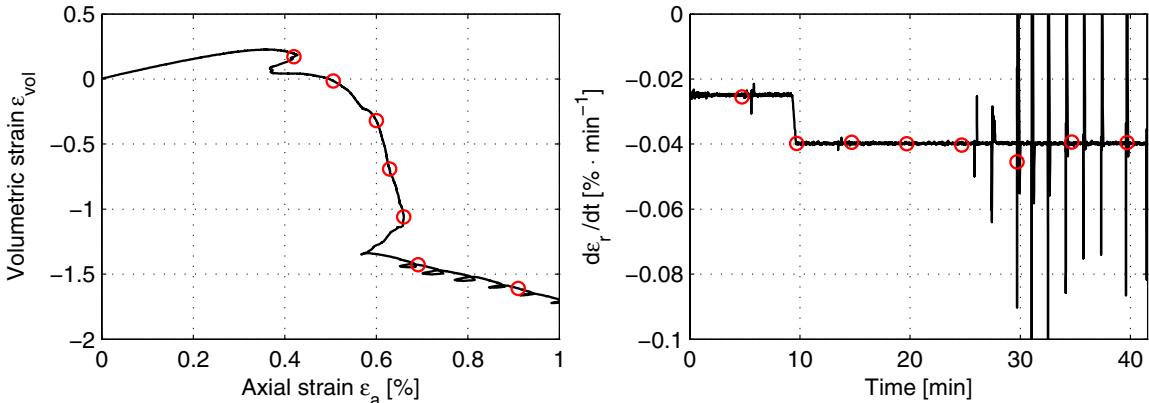
Appendix B

This appendix contains complementary results showing the volumetric strain ϵ_{vol} versus the axial strain ϵ_a and the actual radial strain rate $d\epsilon_r/dt$ versus time. The complementary results for all tests are shown below.

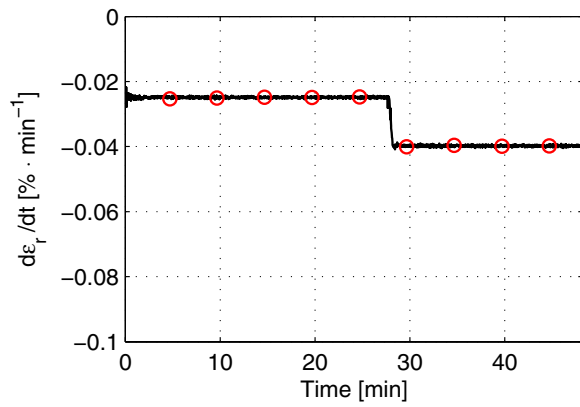
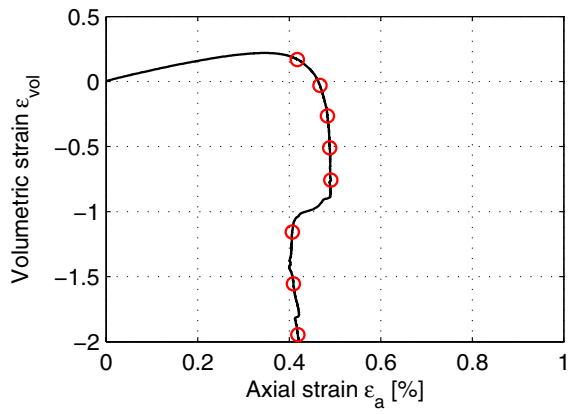
Specimen ID: KLX04A-115-01



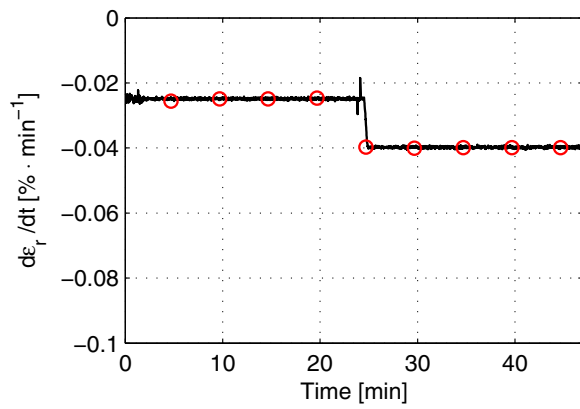
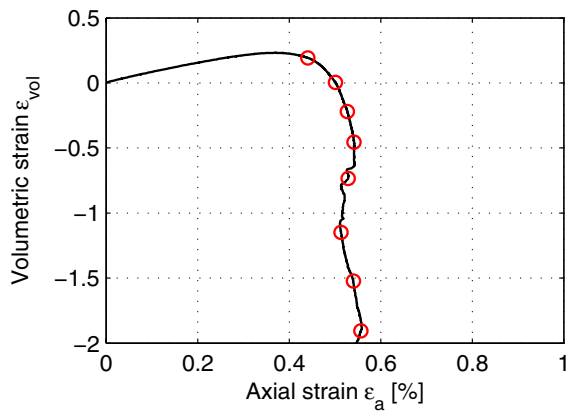
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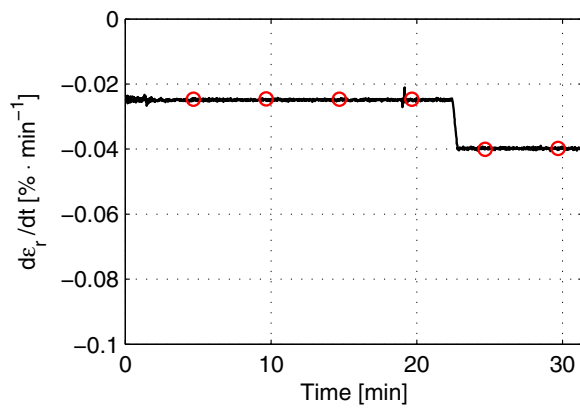
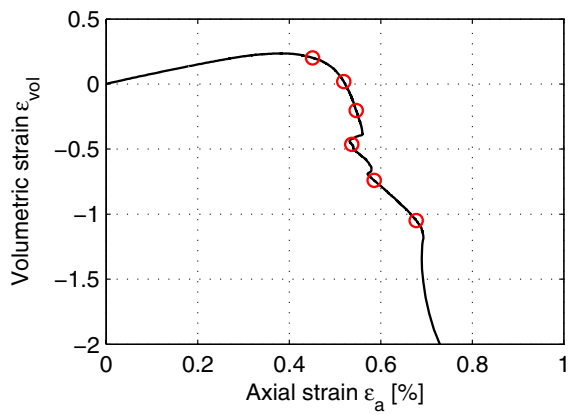
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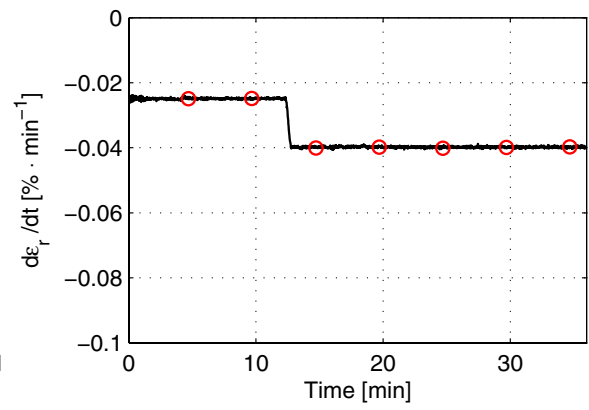
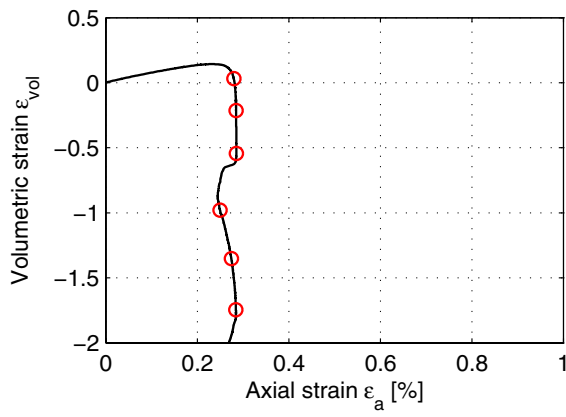
Specimen ID: KLX04A-115-04



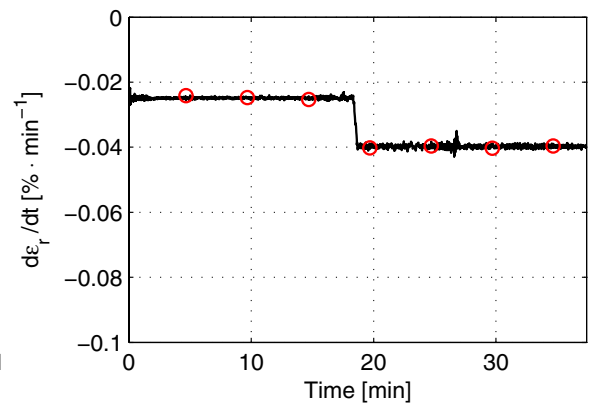
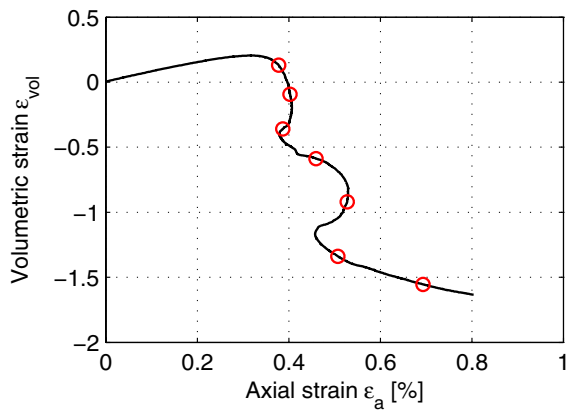
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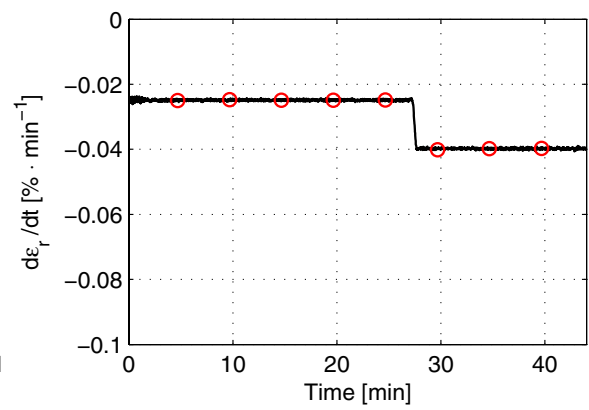
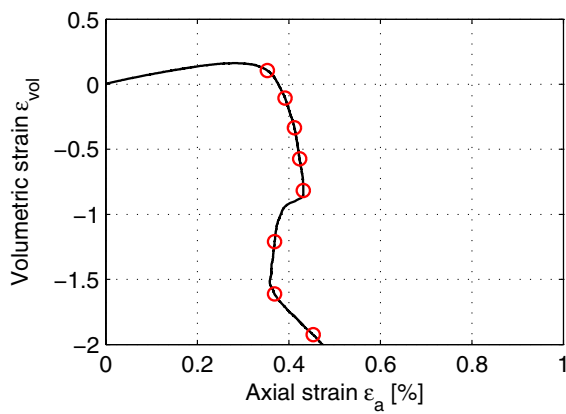
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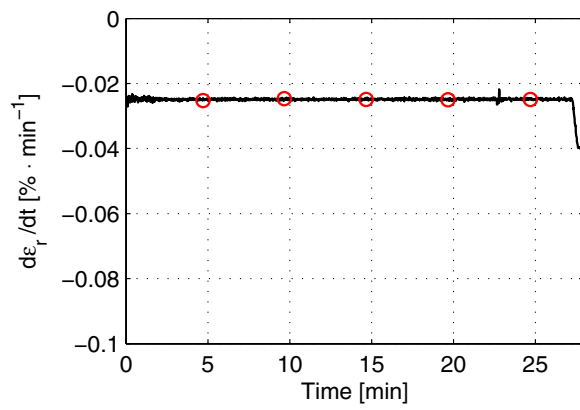
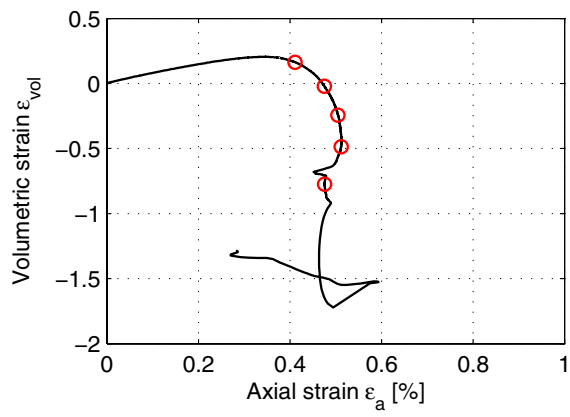
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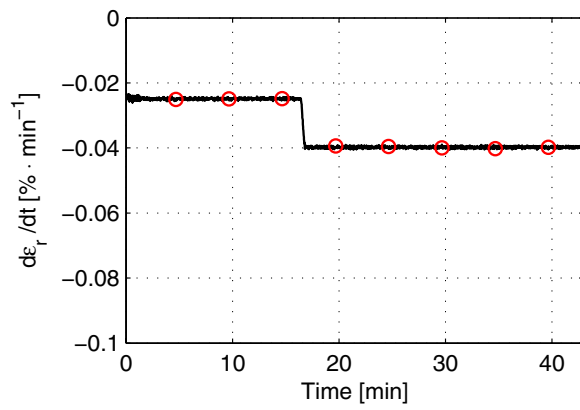
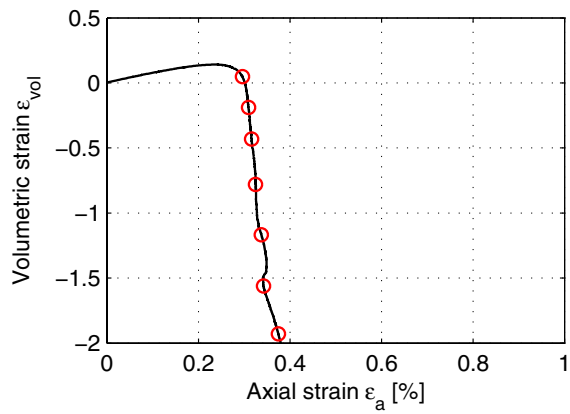
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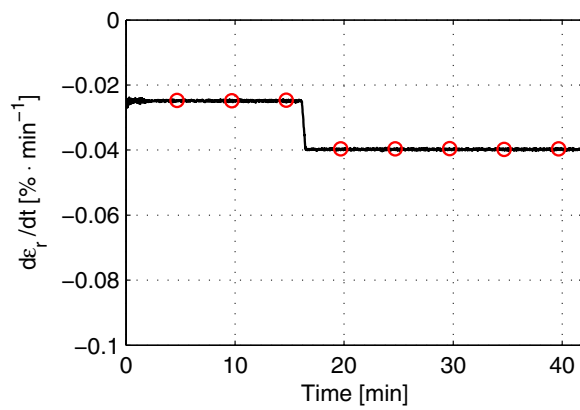
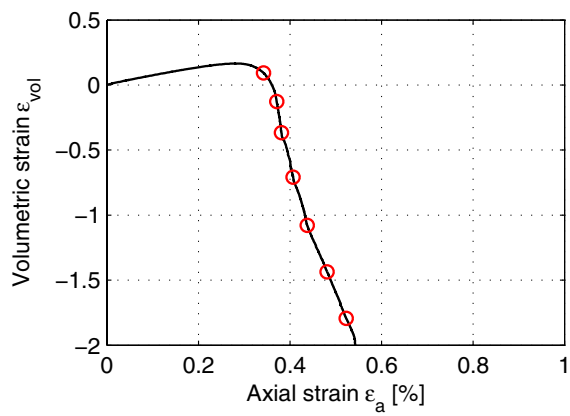
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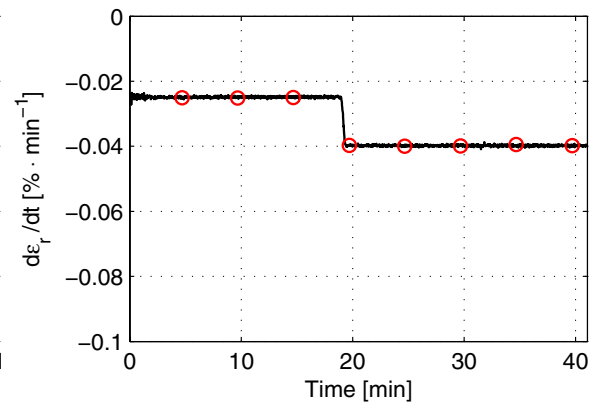
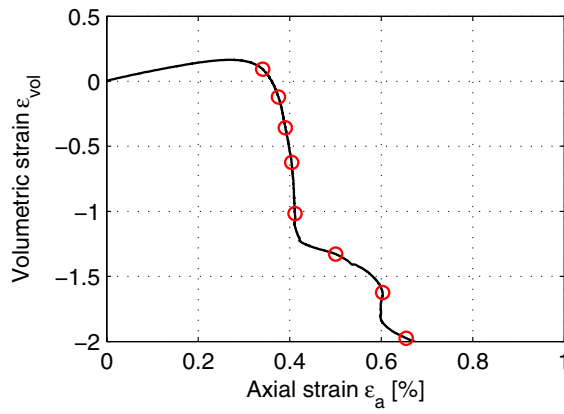
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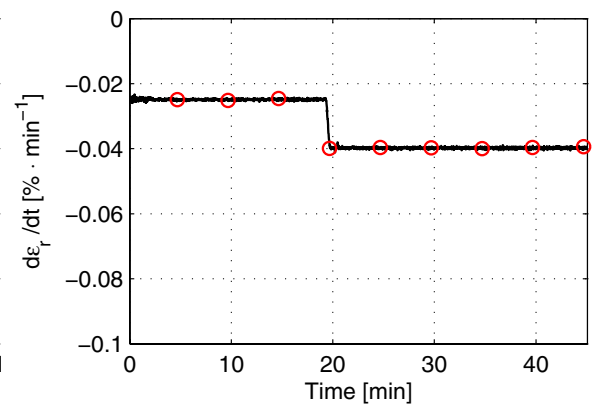
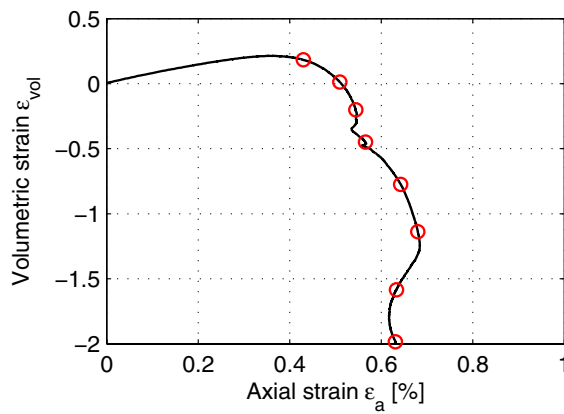
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Specimen ID: KLX04A-115-14



Specimen ID: KLX04A-115-15



Specimen ID: KLX04A-115-16

