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Oskarshamn site investigation

Borehole KLX02

Normal stress and shear tests on joints

Lars Jacobsson

SP Swedish National Testing and Research Institute

November 2004

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Keywords: Rock mechanics, Joint test, Normal stiffness, Shear stiffness, Shear strength, Deformation.

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

Normal loading tests and shear tests on joints on 9 rock specimens from borehole KLX02 in Laxemar have been carried out. The specimens were taken from cores at three depth levels ranging between 316–317 m, 489–501 m and 735–740 m. The rock type was mapped as Ävrö granite.

Two load cycles with a normal loading to 10 MPa were conducted in the normal loading tests on each specimen in order to investigate the joint stiffness in the normal direction. Moreover, three shear cycles were conducted in the shear tests on each specimen; at 0.5 MPa, 5 MPa and 20 MPa constant normal stress level. The peak and residual shear stresses were deduced from the tests. The specimens were photographed before and after the mechanical tests.

The mean value for the peak shear stress and the residual stress were 0.82 MPa and 0.57 MPa respectively for the 0.5 MPa normal stress level and 4.84 MPa and 3.88 MPa respectively for the 5 MPa normal stress level and 16.06 MPa and 13.85 MPa respectively for the 20 MPa stress level.

Sammanfattning

Normalbelastnings- och skjuvförsök har genomförts på 9 stycken naturliga sprickor i bergprov från borrhål KLX02 i Laxemar. Proven har tagits från borrkärnor vid tre djupnivåer 316–317 m, 489–501 m och 735–740 m och var av bergtypen Ävrö granit.

Sprickorna belastades med två lastcykler i normalriktningen med en belastning upp till 10 MPa i normalbelastningsförsöken. Vidare genomfördes tre skjuvcykler på sprickorna under skjuvförsöken där en konstant normalspänning på respektive 0,5 MPa, 5 MPa och 20 MPa användes. Toppvärdet och residualvärdet på skjuvspänningen vid de olika normalspänningsnivåerna bestämdes ur dessa försök. Provobjekten fotograferades före och efter de mekaniska proven.

Medelvärdena för toppvärdet och residualvärdet hos skjuvspänningen i de olika skjuvförsöken låg på respektive 0,82 MPa och 0,57 MPa med 0,5 MPa normalspänning, 4,84 MPa och 3,88 MPa med 5 MPa normalspänning och 16,06 MPa och 13,85 MPa med 20 MPa normalspänning.

Contents

1 Introduction

Normal loading and shear tests on joints have been conducted on specimens sampled from borehole KLX02 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 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 Swedish National Testing and Research Institute (SP). All work is carried out in accordance with the activity plan AP PS 400-03-092 (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 June 2004 and were tested during October 2004. Specimens were cut from cores containing natural fractures and selected based on the preliminary core logging with the strategy to primarily investigate the mechanical properties in joints of the dominant rock types. Two normal loading cycles with loading between 0.5 MPa and 10 MPa was carried out in the normal loading tests in which the normal deformation in the joint was measured. This was followed by three successive shear tests in which the normal stress was kept constant. The normal stress levels were 0.5 MPa, 5 MPa and 20 MPa. The shear deformation was controlled and given a constant deformation rate and the shear stress and the normal deformation in the joint were recorded during the tests. The peak and residual shear stress at each shear cycle were determined from the shear tests. The specimens were photographed before and after the mechanical testing.

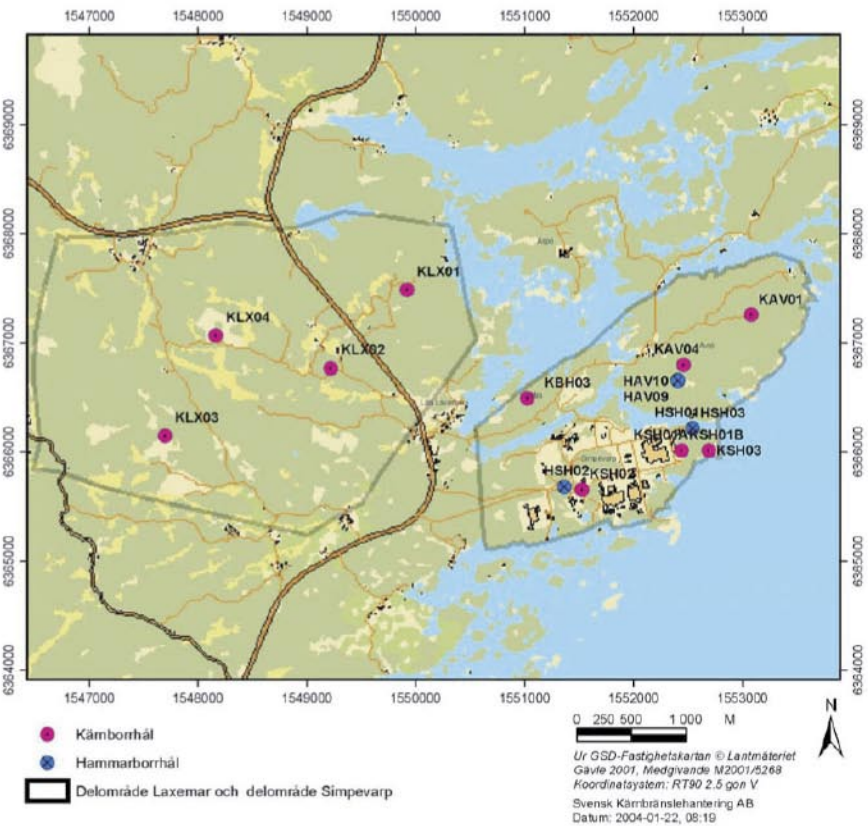


Figure 1-1. *Location of the borehole KLX02 at the Laxemar site.*

The method description SKB MD 190.005e, version 2.0, (SKB internal controlling document) was followed for the sampling and for the normal loading and shear tests. The method description is partly based on the ISRM suggested method /1/.

2 Objective and scope

The purpose of the tests in this report is to determine the mechanical properties of natural fractures in rock specimens. The behavior of the joints is investigated during normal loading and shear loading tests. The aim of the normal loading tests is to determine the relation between the normal stress and the normal deformation in the joints. Further, the joint friction represented by the peak and residual shear stresses together with the dilatancy in the joints during shearing at different constant normal stress levels were obtained from the shear tests. 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

The specimens are from the borehole KLX02, which is an old borehole with a bore depth of 1,700 m.

3 Equipment

3.1 Specimen preparation

A circular saw with a diamond blade was used to cut out and trim the specimens to the final shape. The specimen dimensions were measured by means of a sliding calliper.

The specimens were cast in special holders (one upper and one lower). A device for holding the specimens in a fixed position was used during casting. Further, a specially designed fixture was used to clamp the two halves of the holder in the exact position relative to each other. This is of great importance in order to obtain the correct initial conditions for the tests.

A two-component epoxy mixed with quartz sand was used to cast the specimens. The sand increases the stiffness of the epoxy mix. The specimens were cured in a heat chamber in order to speed up the hardening process, due to quick sedimentation.

A digital camera with 4 Mega pixels has been used to photograph the specimens.

3.2 Mechanical testing

A servo hydraulic testing machine, designed for direct shear tests, has been used for the normal loading and shear tests, see Figure 3-1. The machine has two shear boxes, one upper and one lower. The upper box can be moved vertically and the lower can be moved horizontally. Two actuators, one acting vertically and one acting horizontally, are used to apply the forces in the two directions (degrees of freedoms). Two linear bearings are used for the guidance of the lower box in order to have a controlled linear movement. The maximum stroke is 100 mm in the vertical direction and is +/– 50 mm in the shear direction. The normal and shear displacements are measured by means of LVDTs. The vertical displacement between the shear boxes is measured by four LVDTs, positioned in a square pattern around the specimen, one in each corner. Each of the LVDTs has a measurement range of 5 mm and a relative error less than 1%. The average value of these four LVDTs is used to represent the vertical (normal) displacement presented in the results section. The relative displacement between the shear boxes in the horizontal (shear) direction is measured by one LVDT, which has a 10 mm range and a relative error less than 1%.

The maximum vertical (normal) load that can be applied is 300 kN and the maximum load in the horizontal (shear) direction is +/– 300 kN. Load cells are used to measure the forces in both directions. The accuracy of the load measurement is within 1%. The machine is connected to a digital controller with a computer interface for setting up and running tests.

Figure 3-1. *Equipment for direct shear tests and digital controller unit.*

4 Execution

The normal loading and shear tests were carried out according to the method description SKB 190.005e, version 2.0, (SKB internal controlling document). The test method follows ISRM suggested methods for determining shear strength /1/.

4.1 Description of the samples

The rock type characterisation was made according to Stråhle /2/ 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 and rock type for all specimens.

Identification	Secup (m)	Seclow (m)	Rock type
KLX02-117-1	316.30	316.39	Ävrö granite
KLX02-117-2	316.89	317.00	Ävrö granite
KLX02-117-3	317.40	317.48	Ävrö granite
KLX02-117-4	489.14	489.22	Ävrö granite
KLX02-117-5	492.42	492.53	Ävrö granite
KLX02-117-6	501.87	501.95	Ävrö granite
KLX02-117-8	735.95	736.05	Ävrö granite
KLX02-117-9	737.51	737.62	Ävrö granite
KLX02-117-10	740.72	740.80	Ävrö granite

4.2 Specimen preparation

The specimens are cut out from rock cores. The pieces are shaped and trimmed to obtain a total thickness *h* approximately between 30–35 mm and a maximum length *l* of 60 mm, cf Figure 4-1. The specimens will therefore have similar shape and joint area size.

The specimens are cast in steel holders, which consist of one upper and one lower half, using an epoxy that is reinforced with fine quartz sand in order to increase the stiffness, see Figure 4-2. The specimen halves are positioned relative to each other such that the two specimen pieces best fit together implying that the fracture or joint is optimally closed. This will be termed the zero or the initial position for the shear displacement in conjunction with the shear tests.

One half is cast first by pouring the epoxy into the holder with the specimen held in the correct position. The epoxy is hard enough after one day to fixate the specimen. The second half of the holder is then mounted on top of the first one with a 6 mm gap between the two halves and turned upside down. The second half is cast by pouring epoxy into the holder. After one half to one day, the holders with the cast specimen are put in a heat chamber with 40 °C. The epoxy is fully hardened after three days in the heat chamber and the holders with the specimens are taken out to be cooled down to room temperature.

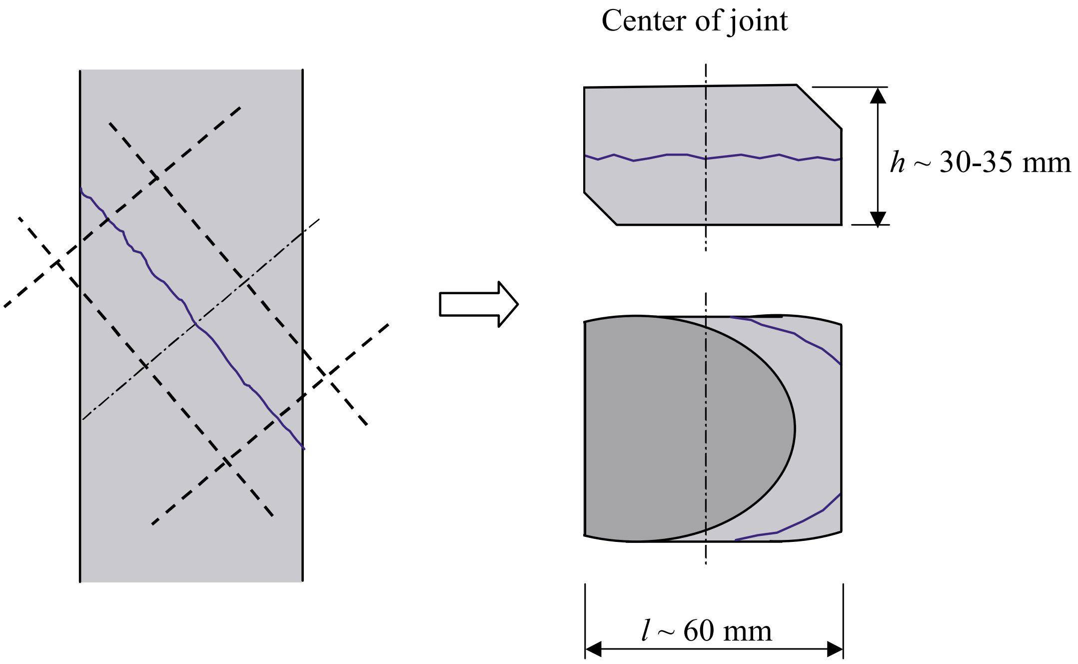


Figure 4-1. *Principle of specimen processing. Left: Cylindrical core containing a joint. The dashed lines show the cutting lines; Right: Specimen after processing.*

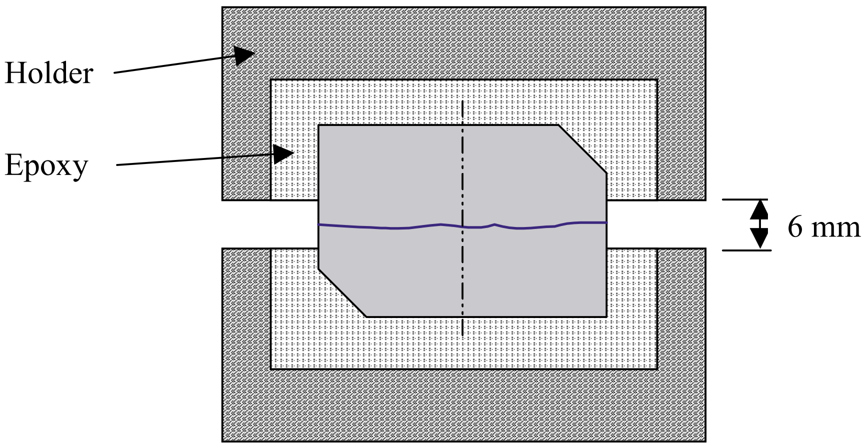


Figure 4-2. *Specimen cast in the specimen holder.*

An overview of the activities during the specimen preparation is shown in the step-by-step description in Table 4-2.

Table 4-2. Activities during the specimen preparation.

Step	Activity
1	Mark the drill cores at the position of the joints that is selected for testing.
2	Cut out the specimens from the cores and trim them to the specified dimensions.
3	Measure the specimen dimensions and calculate the joint surface area.
4	Take digital photos on each specimen.
5	Cast the specimens into the specimen holders.

4.3 Mechanical testing

Two load cycles, with a normal loading between 0.5 MPa and 10 MPa, were conducted in the normal loading tests on each specimen. The normal deformation in the joint was recorded in these tests. Three successive shear tests were carried out directly after the normal loading tests starting from the same initial position in the shear direction as when the normal loading tests were carried out (zero shear displacement). The shear tests were conducted with a constant normal stress, at 0.5, 5 and 20 MPa, respectively. Each joint was sheared with a constant displacement rate to a final displacement value slightly exceeding 2, 3 and 5 mm for the 0.5, 5 and 20 MPa normal stress levels. The shear tests were finished by unloading the shear stress to zero. The normal stress was lowered to 0.2 MPa before the shear position was restored to its starting point (zero shear displacement) for the following shear test. Both the normal and the shear displacements in the joint were recorded in the shear tests.

The program controlling the tests is divided in four parts: one part for the two normal loading cycles and one program each for the three shear tests resulting in four separate data files for each specimen.

A form was filled in for each specimen containing specimen dimensions. Further, the form also contains comments and observations during the different test steps. Moreover, a check list was filled in during the work in order to confirm that the different specified steps have been carried out.

An overview of the activities during the mechanical testing is shown in the step-by-step description in Table 4-3.

Table 4-3. Activities during the mechanical testing.

Step	Activity
1	Mount the specimen holders in the shear testing machine.
2	Perform the normal loading tests with two load cycles. Zero the channels for the normal deformation measurement before the test at 0.5 MPa normal stress. The specified loading/unloading rate is 10 MPa/min.
3	Perform the shear tests at the three constant normal stress levels, 0.5 MPa, 5 MPa and 20 MPa:
	• Apply a normal stress of 0.5 MPa and zero the deformation channels.
	• Increase the normal stress to the prescribed value for the actual test.
	• Apply a shear deformation with a rate of 0.5 mm/min and shear until the shear displacement reaches 2, 3 or 5 mm respectively for the 0.5 MPa, 5 MPa and 20 MPa stress levels.
	• Unload the shear stress to zero.
	• Unload the normal stress to 0.2 MPa and restore the shear deformation to zero (initial position).
	Repeat this for the three shear cycles.
4	Take out the specimens from the shear boxes.
5	Take digital photos on each specimen.
6	Store the test results on the computer network.

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 peak and residual shear stresses were determined, has been carried out in the program MATLAB /3/. Moreover, MATLAB was used to produce the diagrams shown in Section 5.1 and in Appendix A. The summary of results in Section 5.2 with tables containing mean value and standard deviation of the different parameters 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 result parameters we begin with the normal σ_N and shear stresses σ_S, which are defined as

$$\sigma_N = \frac{F_N}{A} \quad \text{and} \quad \sigma_S = \frac{F_S}{A}$$

where F_N is the normal force and F_S is the shear force acting on the joint and A is area of the joint. The peak value σ_{SP} and the residual value σ_{SR} of the shear stress σ_S on each of the three shear cycles are determined. The peak value is defined as the maximum value during the whole shear cycle. The residual value is defined as the mean value of the shear stress of the last 0.5 mm of the shear cycle before the unloading of the shear stress for the 0.5 and 5 MPa normal stress levels and the last 1 mm for the 20 MPa normal stress level. The actual shear force is fluctuating up and down caused by a stick-slip response that is obtained during the shear process due to the uneven surfaces in the joints. The shear stress that is used when the residual value is evaluated, is defined as the envelope that is obtained by interconnecting the sub-peaks that are obtained during the shearing. The distance between the sampled sub-peak points during the tests is quite coarse which makes the mean value calculation less accurate. New data points are therefore added in the interval for the mean value calculation with a linear interpolation if the distance in the shear direction between the sampled sub peaks is less than 0.01 mm. The new points are equidistantly distributed and the number of points new points that are created are determined with the criteria that the distance of the added points should be just less or equal to 0.01 mm. The normal and shear displacements are denoted as δ_N and δ_S, respectively.

A part of the measured normal deformation in the normal loading tests and a part of the measured shear deformations in the shear tests belong to the deformations in the epoxy, in the holders and shear boxes and in the contact surfaces between the specimen holders and the shear boxes. The deformation measured during the normal loading test not belonging to the deformation in the joints is denoted the system deformation $\delta_{N,system}$. By knowing the system deformation, the joint deformation can be obtained as

$$\delta_{N,joint} = \delta_{N,total} - \delta_{N,system} \tag{1}$$

where $\delta_{N,total}$ is the normal displacement registered during the normal loading tests containing the joint displacement $\delta_{N,joint.}$ The system deformation in the normal loading test has significance on the obtained results and will be thoroughly discussed below. The system deformations during the shear tests are of less significance for the results and no correction is made.

One normal loading test consisting of two load cycles with a normal stress going between 0.5 and 10 MPa, where a steel specimen was used instead of a rock specimen, was carried out as a reference test in order to determine the magnitude of the deformation in the system (epoxy and contact areas). The steel specimen had quadratic cross section 50×50 mm and 30 mm height. This yields a total epoxy layer of 20 mm thickness between steel specimen and the top and bottom surfaces in the holders. The dimensions of the steel specimen were chosen such that the cross sectional area is similar to the area of the joints in the rock specimens. Furthermore, the height of the steel specimen was chosen in the same order as the height of the rock specimens. This was done to obtain similar thickness of the epoxy layers in the normal loading direction in both cases in order to get values of the system deformation with the same magnitude. The system deformations in the reference test can be estimated as

$$\delta_{\text{N,system}} = \delta_{\text{N,total}} - \delta_{\text{N,steel}} \quad (2)$$

where

$$\delta_{\text{N,steel}} = \frac{\sigma_{\text{N}}}{E} \cdot t_{\text{steel}}$$

using E = 210 GPa and t_{steel} = 30 mm. The result from the reference test in which the system deformation is computed according to (2) is shown in Figure 4-3.

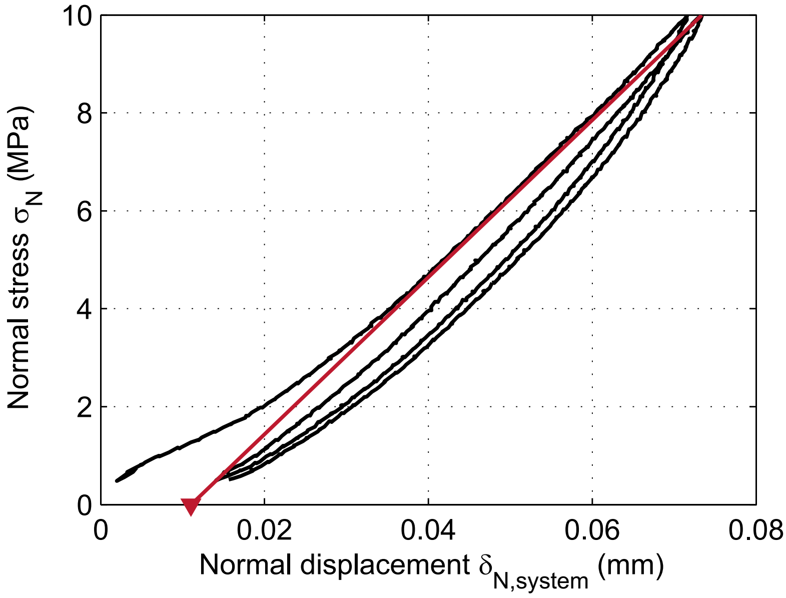


Figure 4-3. *Results from a normal loading test with a steel specimen cast in epoxy. The black curve is showing the results from the tests where the steel deformation has been subtracted from the results. The red line is representing the secant of the loading curve during the second load cycle is intersecting the points at full unloading and full loading. The extension of the line is intersecting the zero stress level at the displacement* $\delta_{N,0.}$ *This point is regarded as a theoretical starting point of the second load cycle and is marked with a filled triangle in the figure.*

It is seen that the response during loading and unloading displays a non-linear behaviour. Moreover, a large part of the permanent deformation is developed during the first load cycle. This can be seen both in the reference test and in the tests on joints. The epoxy layers deform and cause residual deformations after unloading. The different contact areas deform as well. The first load cycle can thus be considered as a conditioning load cycle. The residual deformation is only slightly increasing during the second load cycle. The results from the second load cycle are the most suitable for finding an appropriate correction of the results. The results will be corrected according to (1). Further, the results from the second load cycle are most likely most suitable for evaluating the behaviour in the joints as well. We will use the data from the second load cycle in the reference test to account for the system deformations in the joint tests.

The test results will be arranged such that a supposed starting point of the second load cycle starts from zero normal displacement at complete unloading, i.e. $\sigma_{\mathrm{N}} = 0$. In order to do so we first make an assumption that the point at complete unloading before the loading at the second load cycle is obtained as the linear extension of a secant line, which is drawn between the experimentally obtained starting and end points of the loading curve for the second cycle. The normal deformation in the point when $\sigma_{\mathrm{N}} = 0$ is denoted $\delta_{\mathrm{N,0}}$. This is shown in Figure 4-3. Hence, the data can be shifted by subtracting the value $\delta_{\mathrm{N,0}}$ from normal displacement results. The maximum normal displacement during the second load cycle when both the loading and the deformation start from zero is denoted $\delta_{\mathrm{N,max}}$.

Normalized normal stress and normal deformation are introduced as

$$\bar{\delta}_{\mathrm{N}} = \frac{\delta_{\mathrm{N}}}{\delta_{\mathrm{N,max}}} \quad \text{and} \quad \bar{\sigma}_{\mathrm{N}} = \frac{\sigma_{\mathrm{N}}}{\sigma_{\mathrm{N,max}}} \tag{3}$$

where $\sigma_{\mathrm{N,max}} = 10$ MPa is given in the normal loading tests and $\delta_{\mathrm{N,max}}$ was defined above. The results from the reference tests using the normalized normal stress and normal deformation are shown in Figure 4-4.

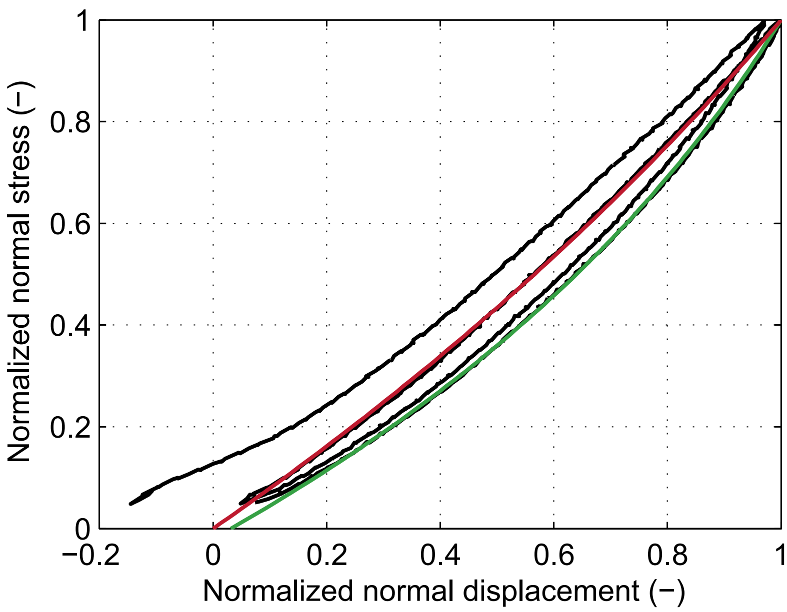


Figure 4-4. *Results from normal loading test on a steel specimen with normalized results parameters. The black curve is showing the results from the tests where the steel deformation has been subtracted from the results. The red and the green curves are showing the fitted approximating functions for the loading and unloading responses during the second load cycle.*

The results from the reference test with the two load cycles are divided into four segments: loading 1, unloading 1, loading 2 and unloading 2. The normalized values of the loading and the unloading response at the second load cycle can be approximated with an exponential expression according to

$$\bar{\delta}_{\mathrm{N}} = A\left[1 - \exp\left(-B \cdot \bar{\sigma}_{\mathrm{N}}\right)\right] \tag{4}$$

where A and B are constants that are determined from the experiments. It is found that A = 2.43 and B = 0.53 are suitable for the loading curve and A = 1.49 and B = 1.05 are suitable for the unloading part of the second load cycle. The approximating curves together with the experimental results are shown in Figure 4-4.

The thickness of the rock specimens with joints is different from specimen to specimen. This means that the thickness of the epoxy layer is shifting as well. It is fair to assume that the system stiffness is dependent on the thickness of the epoxy layer. In order to account for that we assume a linear dependence of the maximum deformation according to

$$\delta_{\mathrm{N,max}} = \frac{t_{\mathrm{epoxy}}}{t_{\mathrm{epoxy\ ref}}} \cdot \delta_{\mathrm{N,max\ ref}} \tag{5}$$

where $t_{\mathrm{epoxy\ ref}}$ and $\delta_{\mathrm{N,max\ ref}}$ are the values obtained from the reference test. Finally, the system deformation in (1) is obtained by rewriting (4) as

$$\delta_{\mathrm{N,system}} = A\left[1 - \exp\left(-B \cdot \bar{\sigma}_{\mathrm{N}}\right)\right] \cdot \delta_{\mathrm{N,max}} \tag{6}$$

The results presented in Section 5 are processed segment-by-segment according to the methodology outlined above using (1), (3), (5) and (6), in order to get the true joint deformations.

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 both on unprocessed raw data obtained from the testing and processed data and were reported to the SICADA database, FN 236. 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

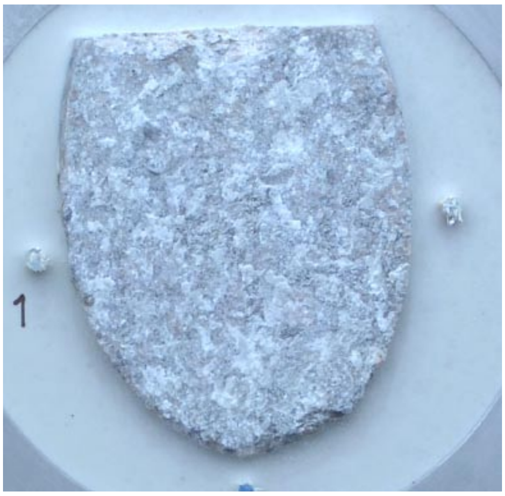
The specimens and joints before casting and after testing are shown on pictures. Comments on observations appeared during the testing are reported. The results from the normal loading tests are shown in the upper diagrams, the results from shear tests are shown in the middle and the lower diagrams. The results from the shear tests for the three normal stress levels are displayed in black (0.5 MPa), green (5 MPa) and blue (20 MPa). Furthermore, the red triangle markers show the peak shear stresses and the red square markers show the residual stresses.

It should be remarked that the normal deformations pertinent to the normal loading tests displayed in upper diagrams have been adjusted by subtracting system deformations, cf Section 4.5. The original results, i.e. the actual measured data, from the normal loading tests, are shown in Appendix A.

Specimen ID: KLX02-117-1

Before mechanical test

After mechanical test

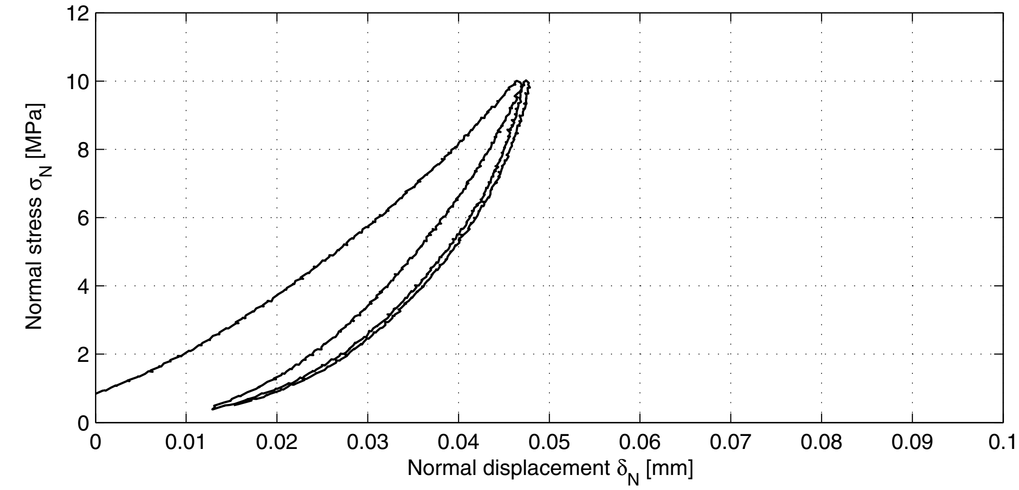


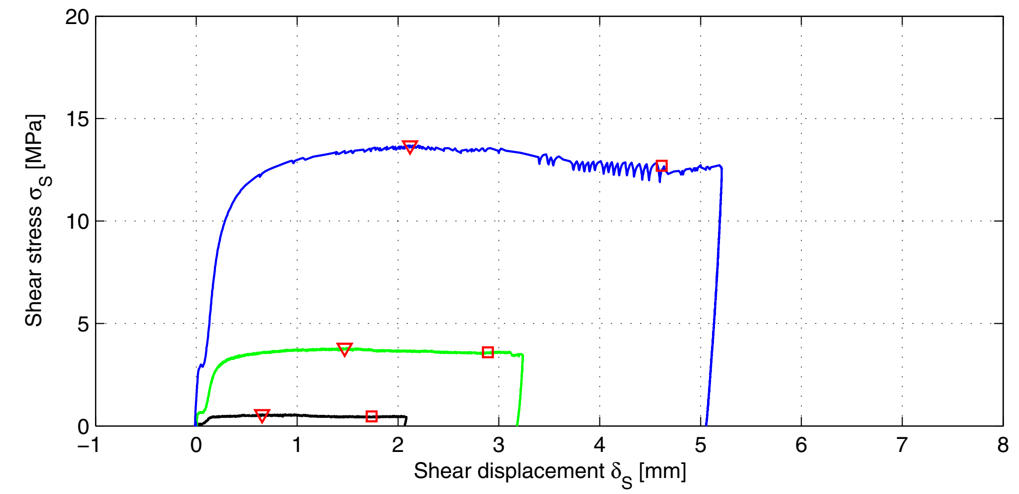
Comments The normal stress decreased to 0.4 MPa in the very beginning.

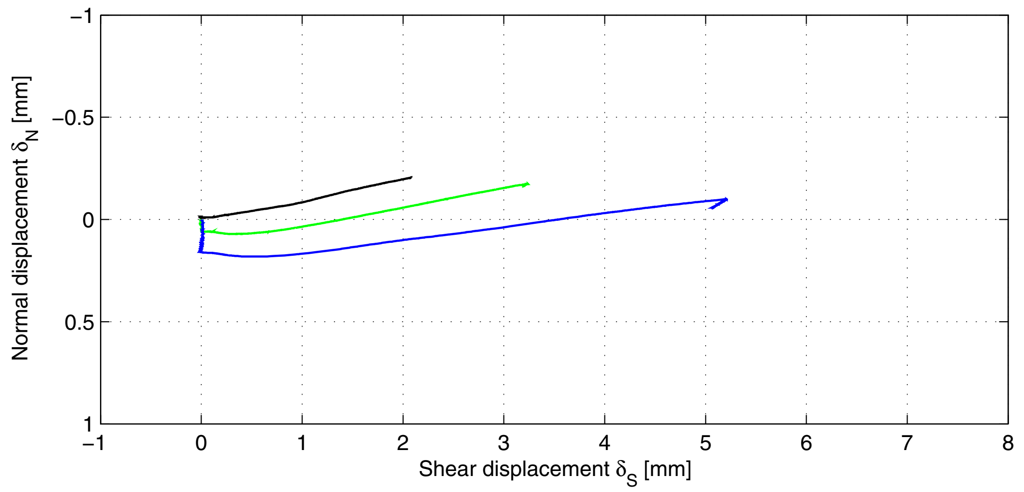
Specimen ID: KLX02−117−01

Joint area : 22.9 cm^2

Specimen height : 34.8 mm



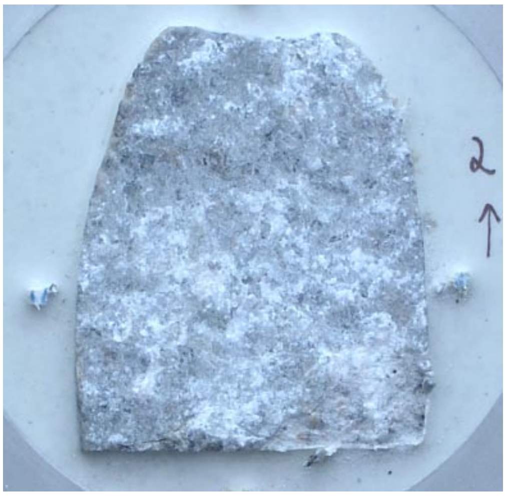




Specimen ID: KLX02-117-2

Before mechanical test

After mechanical test

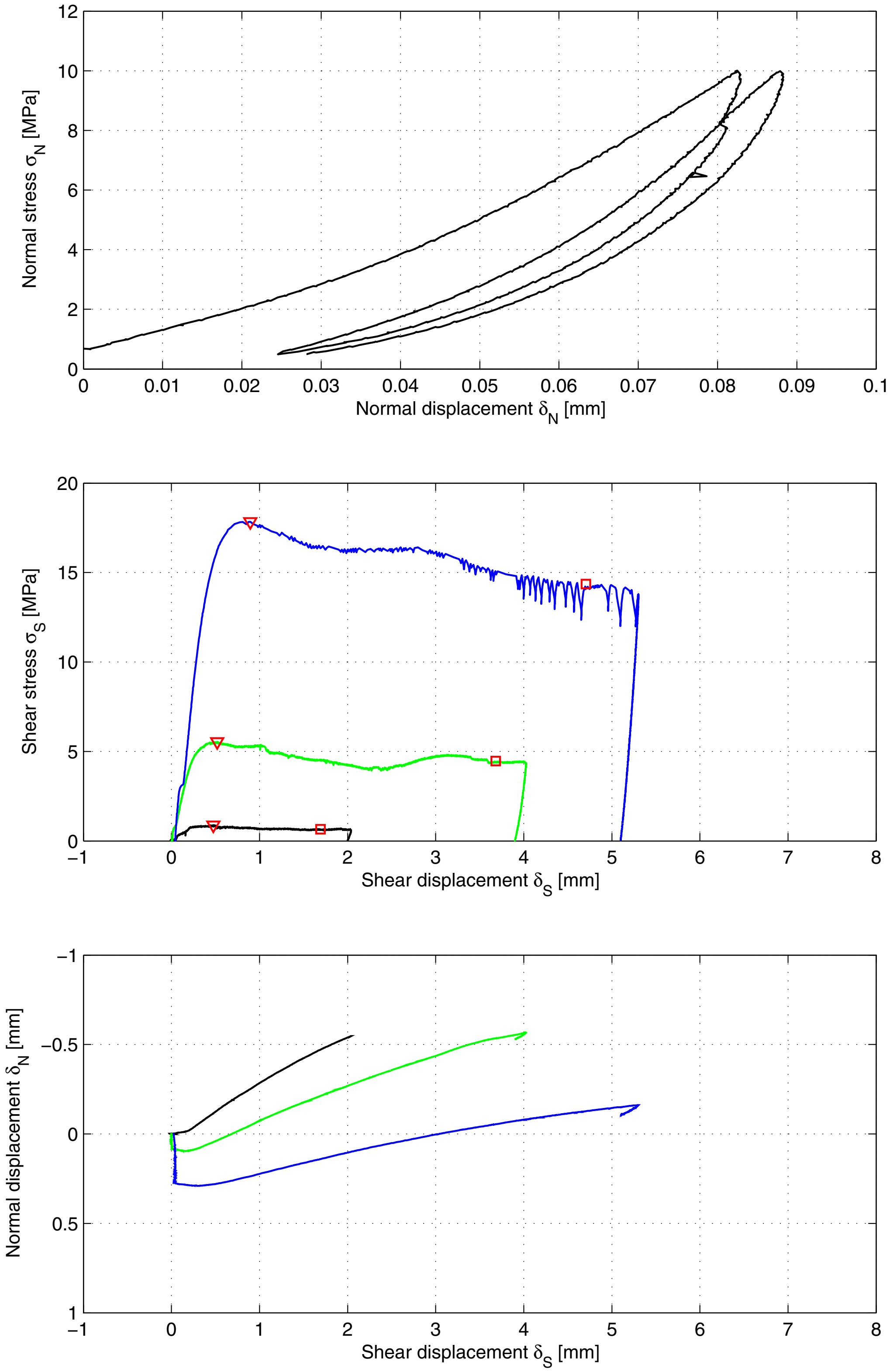


Comments Click sounds was heard after 4 mm shearing at the 20 MPa normal stress level.

Specimen ID: KLX02−117−02

Joint area : 23.2 cm^2

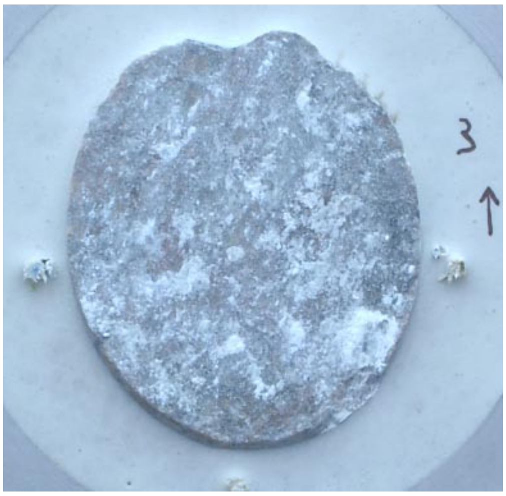
Specimen height : 35 mm

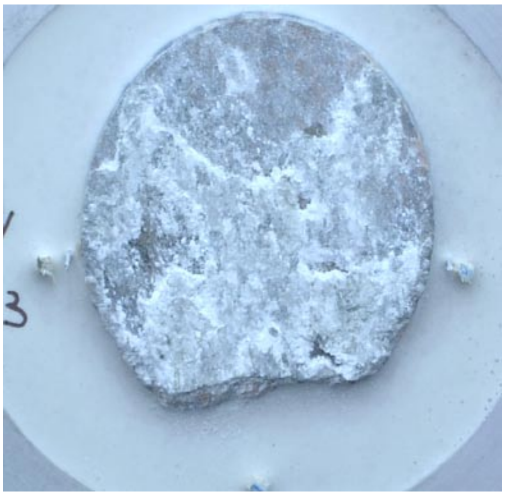


Specimen ID: KLX02-117-3

Before mechanical test

After mechanical test



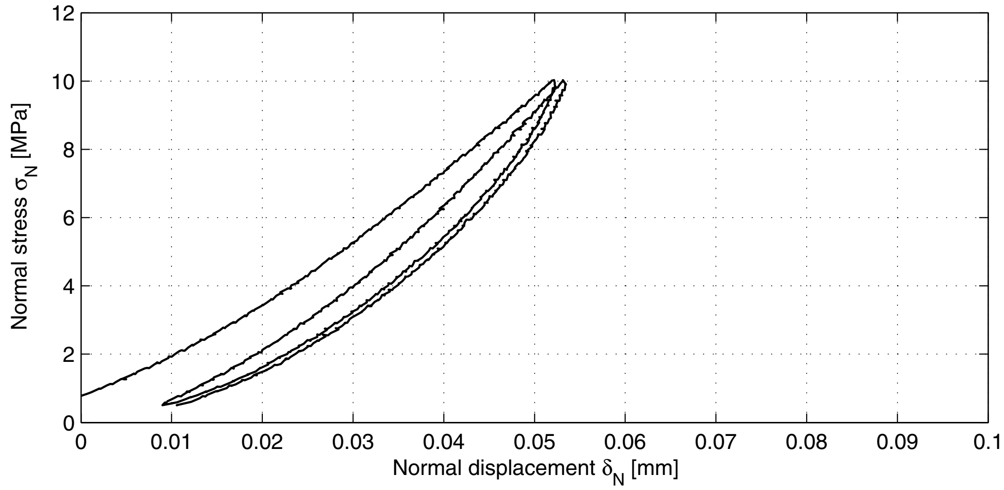


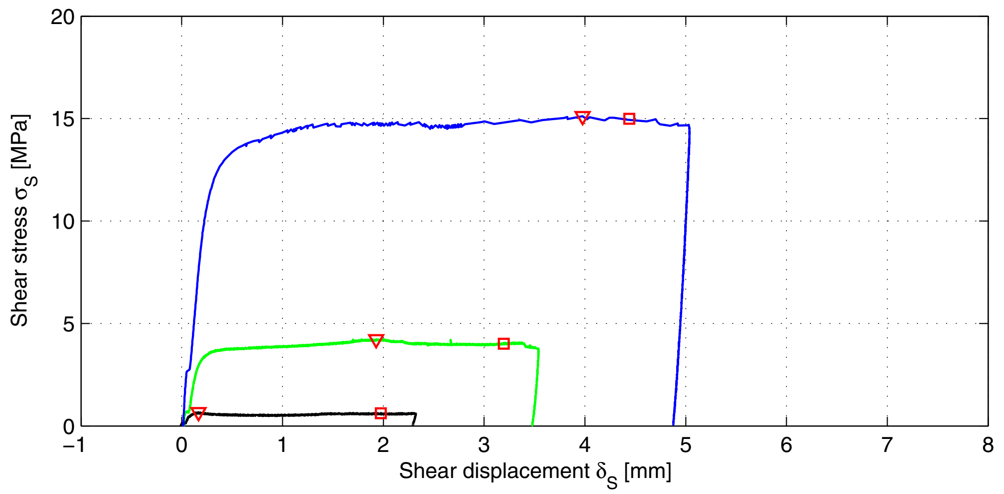
Comments

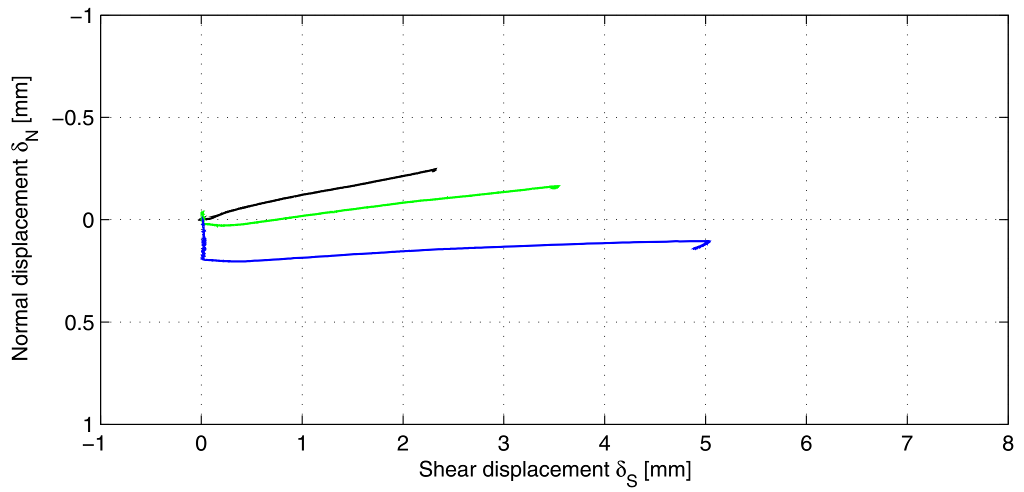
Specimen ID: KLX02−117−03

Joint area : 20.5 cm^2

Specimen height : 35 mm



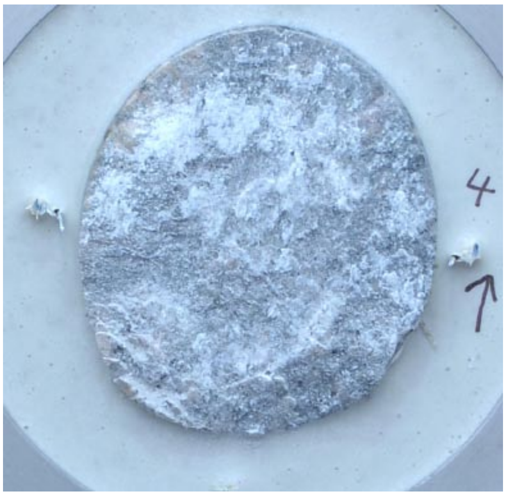


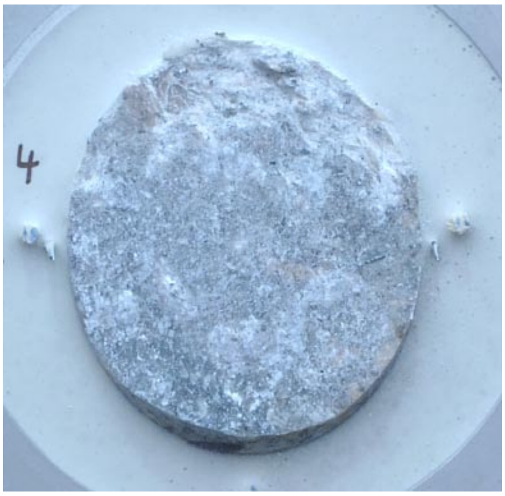


Specimen ID: KLX02-117-4

Before mechanical test

After mechanical test



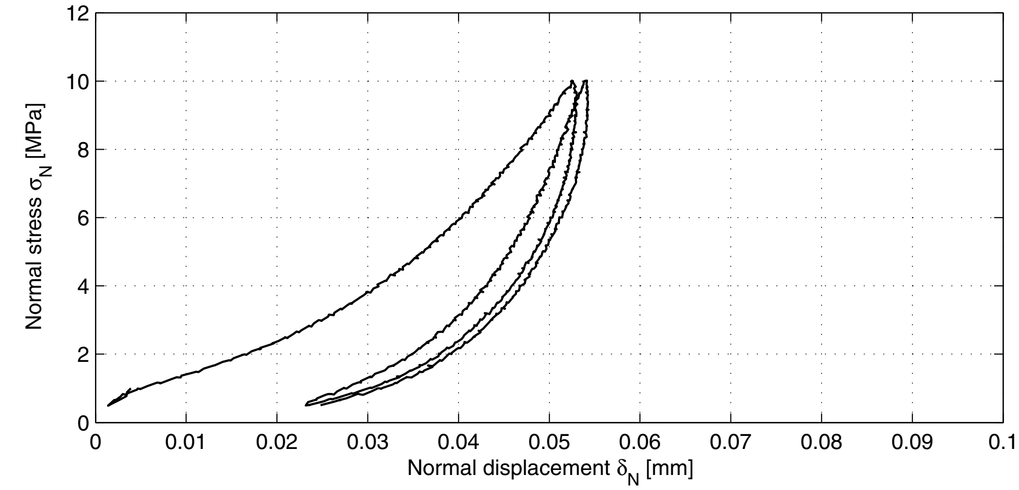


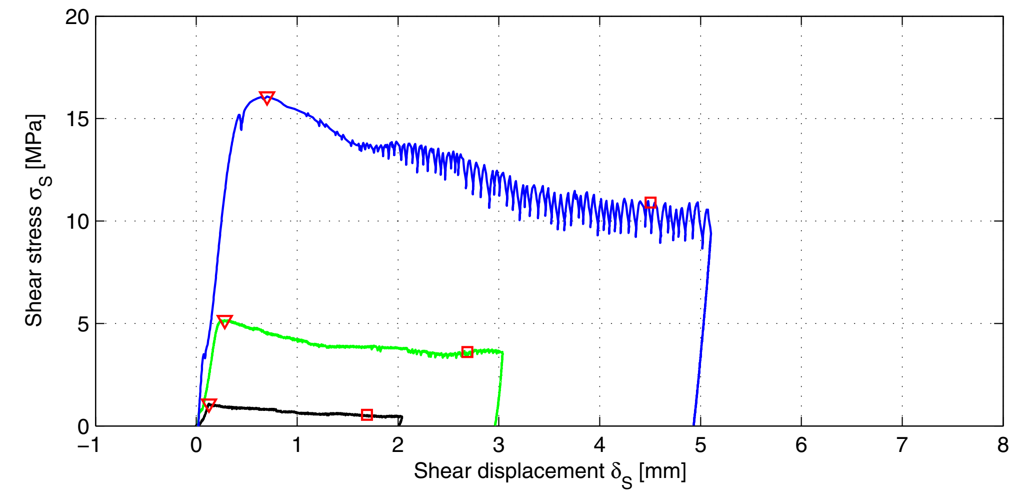
Comments Click sounds was heard after approximately 1.8 mm shearing at the 20 MPa normal stress level.

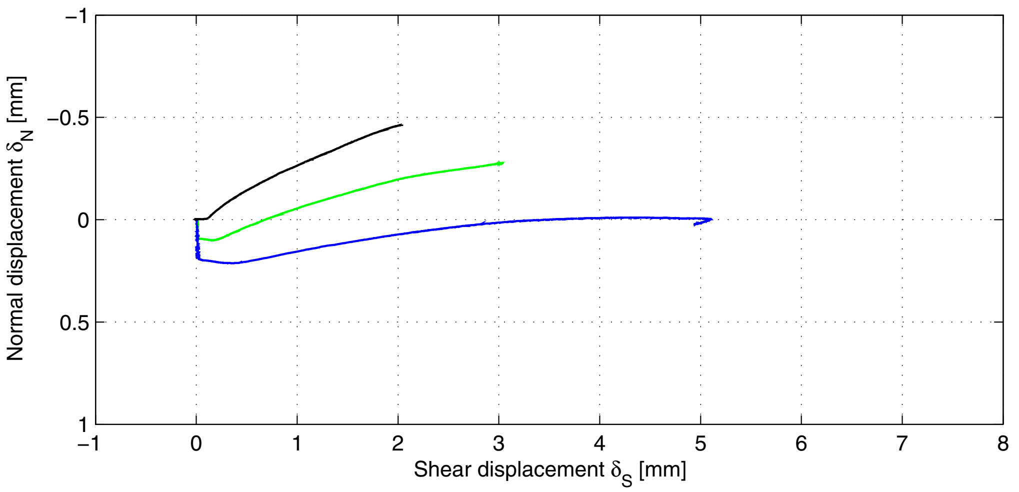
Specimen ID: KLX02–117–04

Joint area : 20.3 cm^2

Specimen height : 32.1 mm



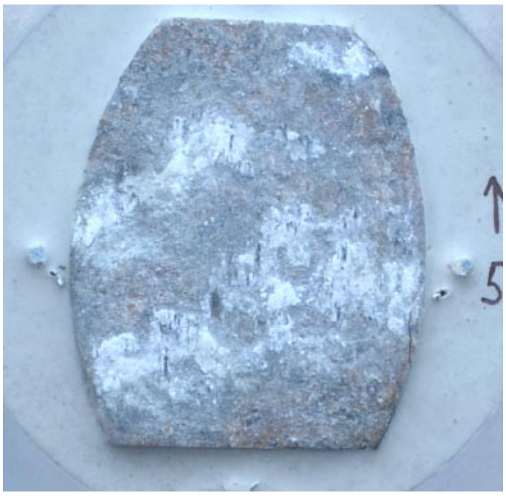


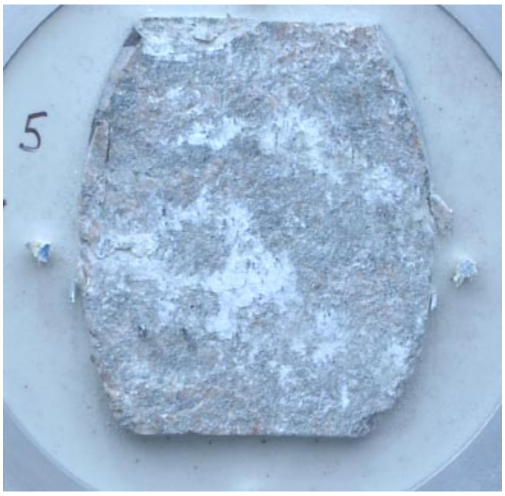


Specimen ID: KLX02-117-5

Before mechanical test

After mechanical test



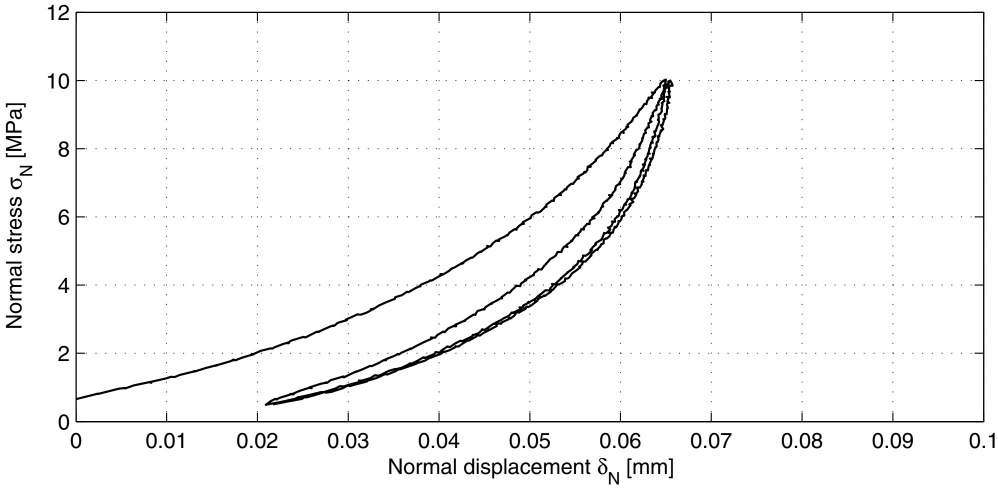


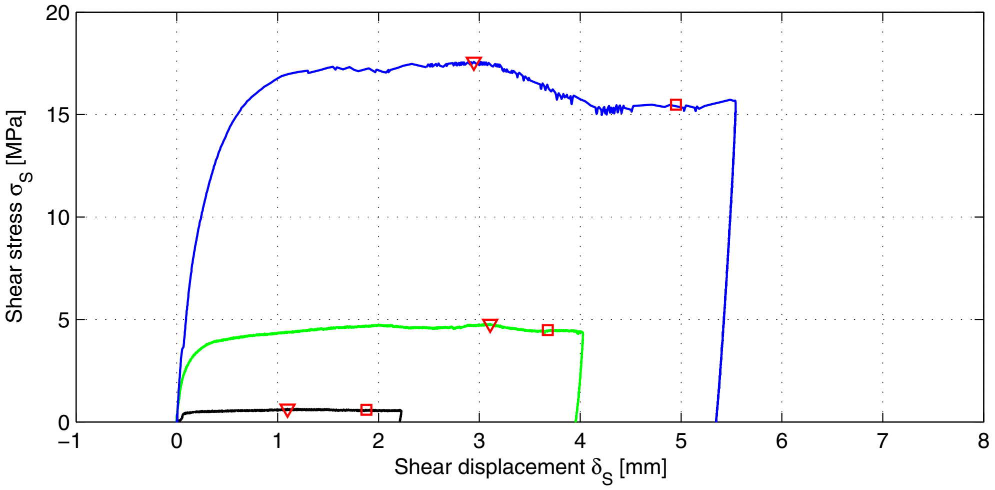
Comments

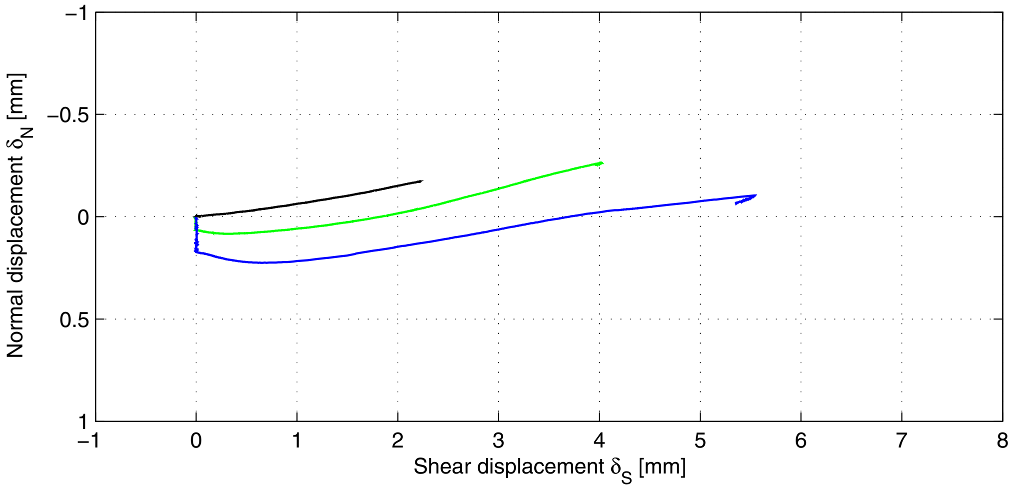
Specimen ID: KLX02−117−05

Joint area : 23.6 cm^2

Specimen height : 34 mm

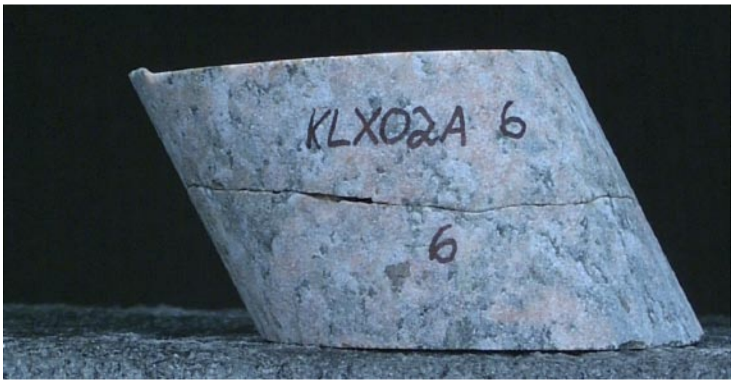




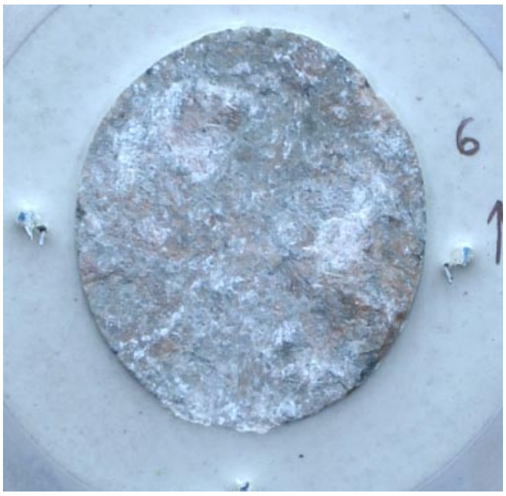


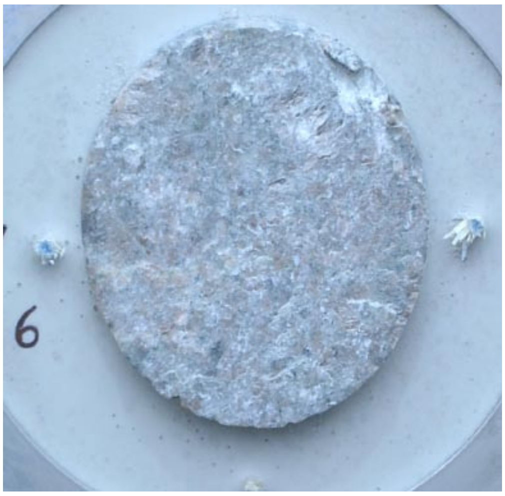
Specimen ID: KLX02-117-6

Before mechanical test



After mechanical test



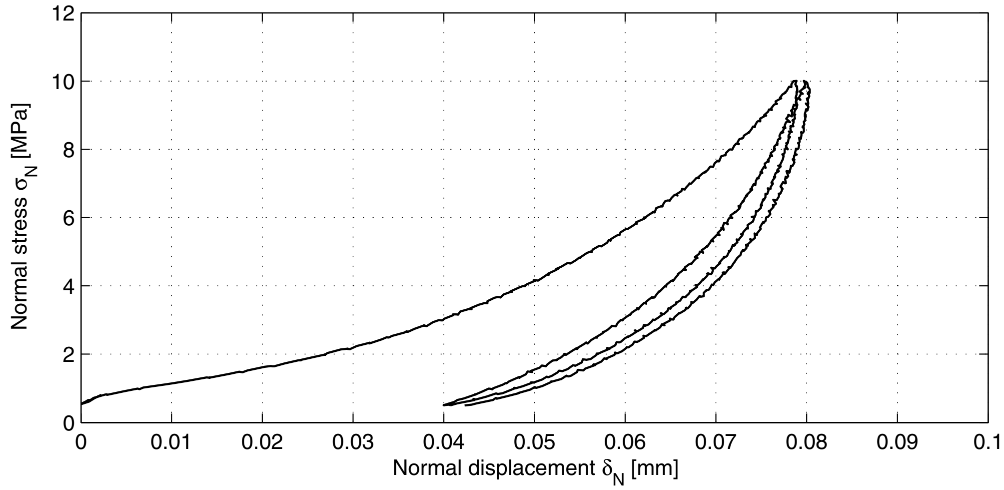


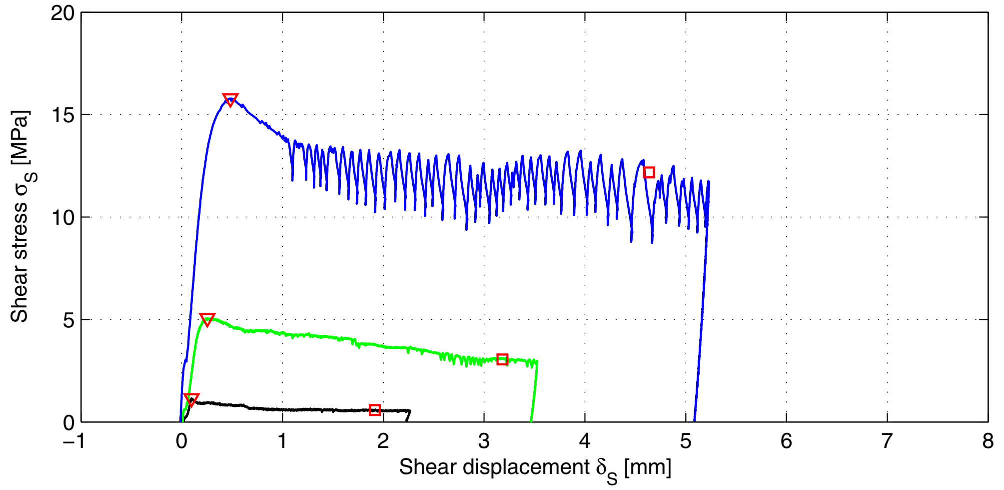
Comments Click sounds was heard from 1–5 mm shearing at the 20 MPa normal stress level.

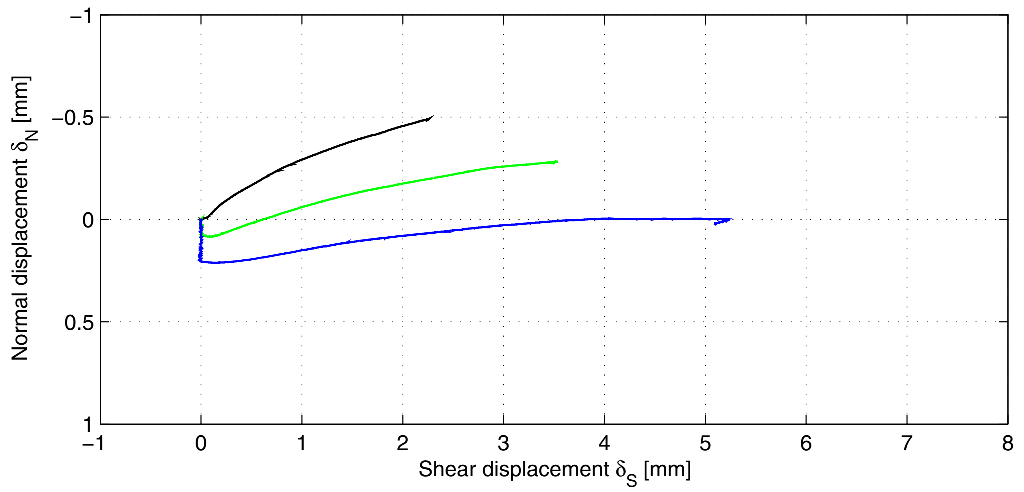
Specimen ID: KLX02−117−06

Joint area : 19.7 cm^2

Specimen height : 32.1 mm



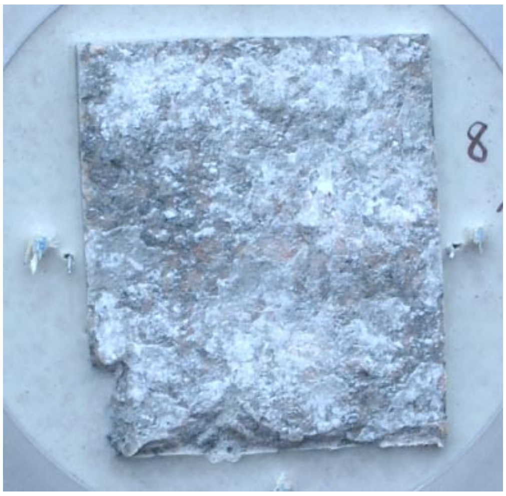


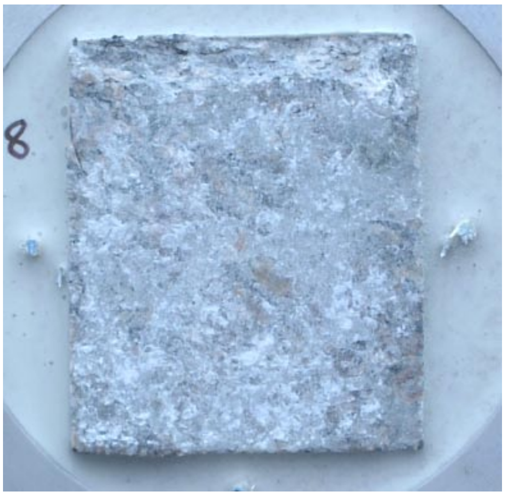


Specimen ID: KLX02-117-8

Before mechanical test

After mechanical test



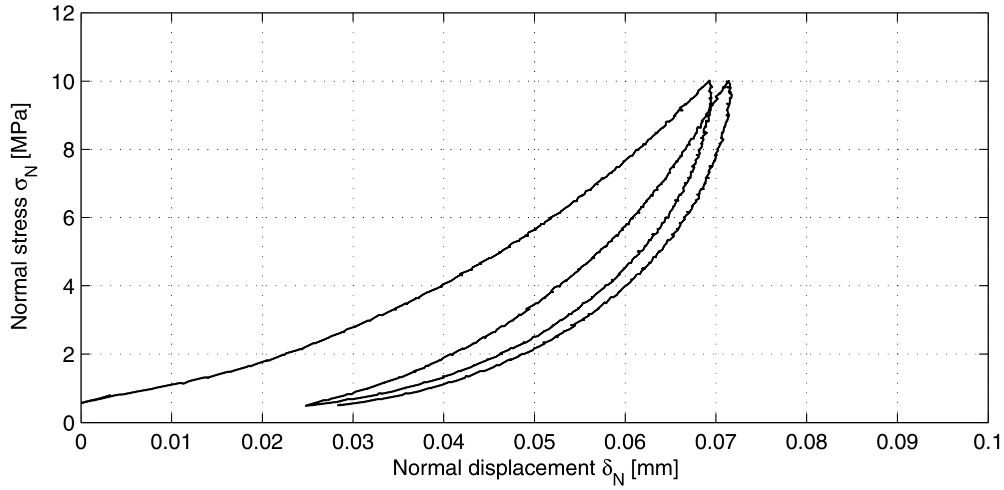


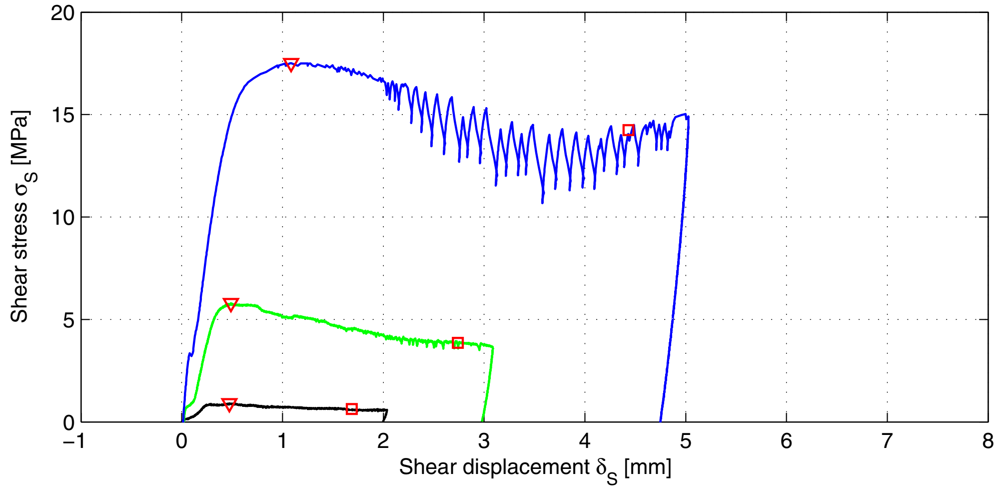
Comments Click sounds was heard after approximately 2 mm shearing at the 20 MPa normal stress level.

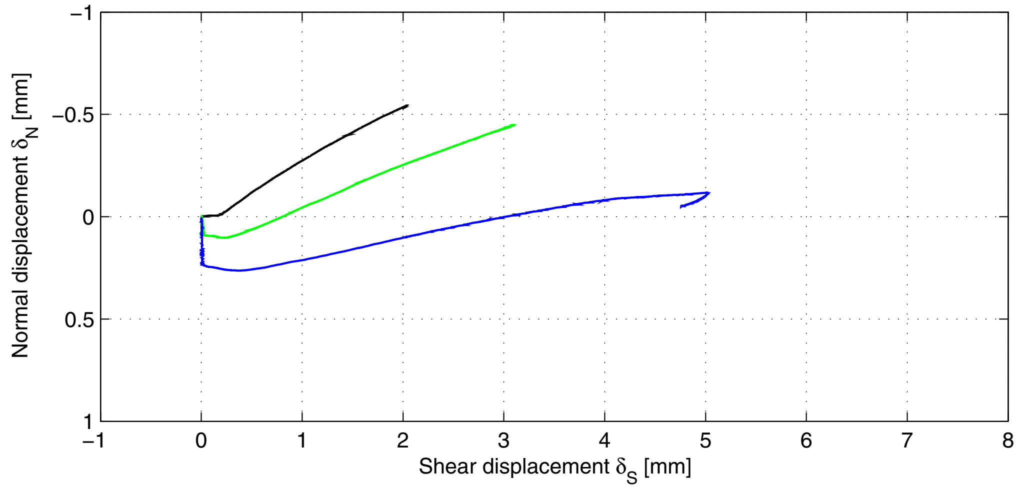
Specimen ID: KLX02−117−08

Joint area : 25.9 cm^2

Specimen height : 34 mm



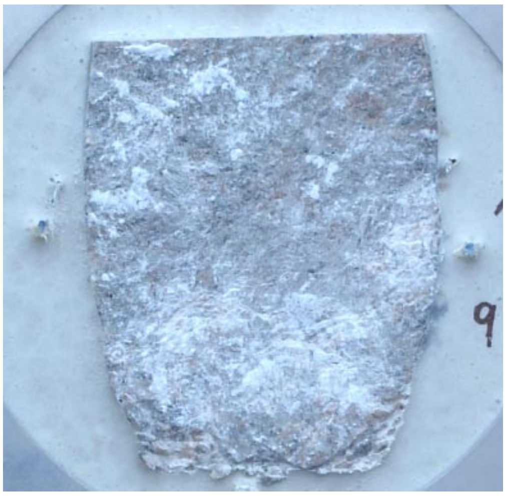




Specimen ID: KLX02-117-9

Before mechanical test

After mechanical test

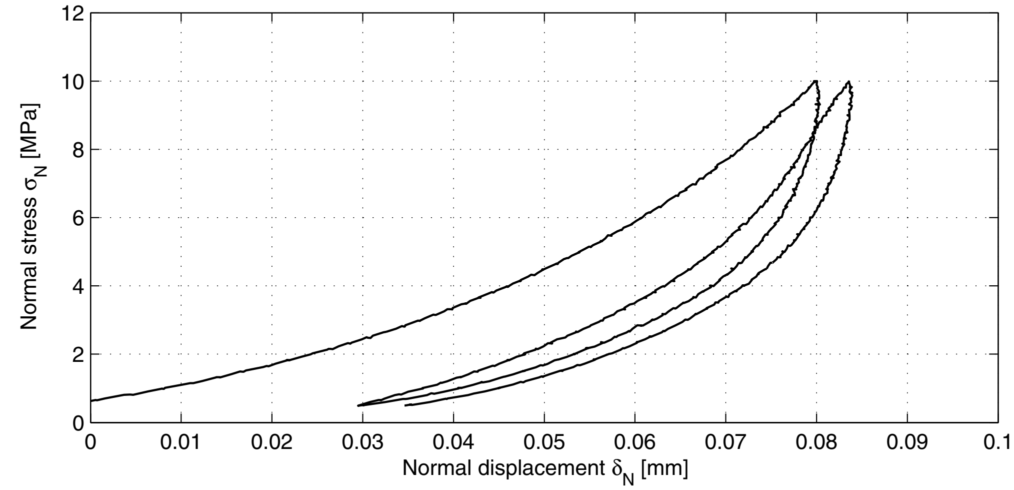


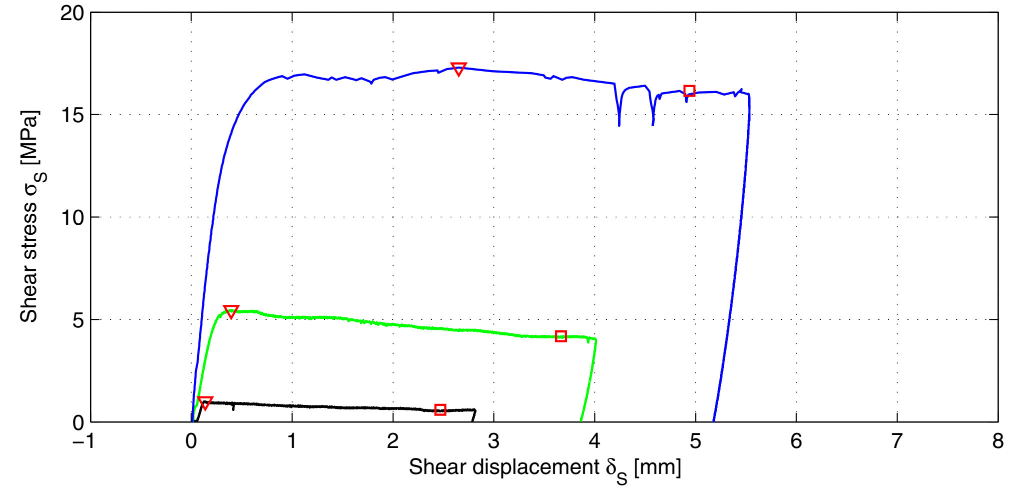
Comments A sudden drop of the shear stress was observed at approximately 0.4 mm shear deformation at the 0.5 normal stress level.

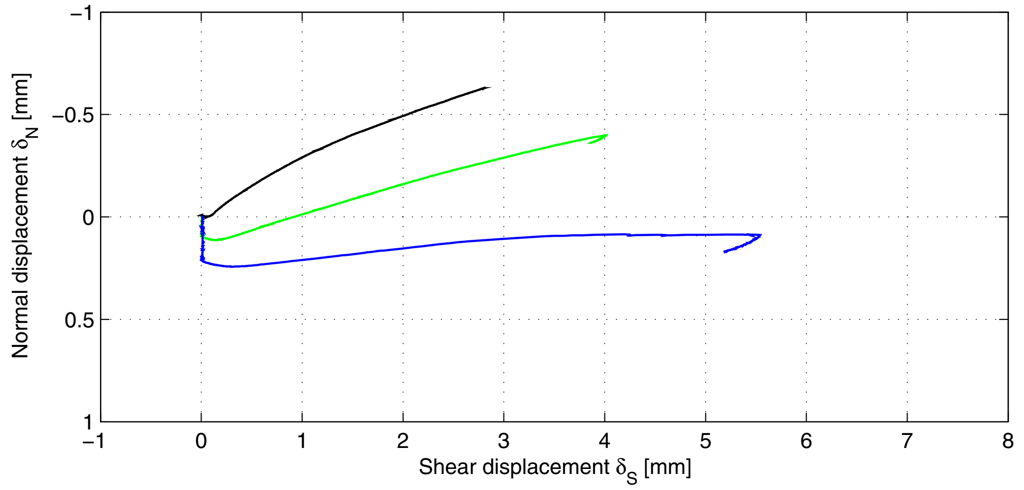
Specimen ID: KLX02−117−09

Joint area : 24.8 cm^2

Specimen height : 34 mm

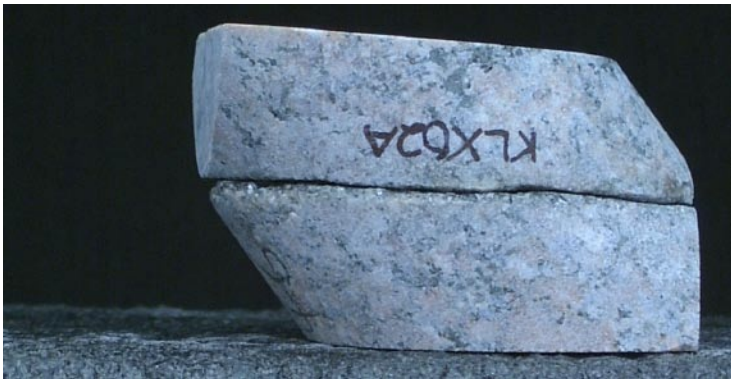




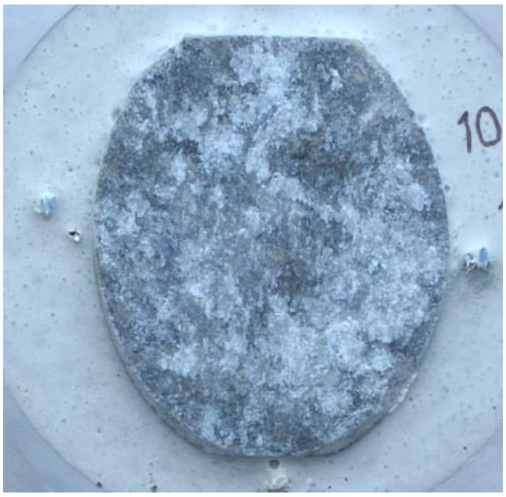


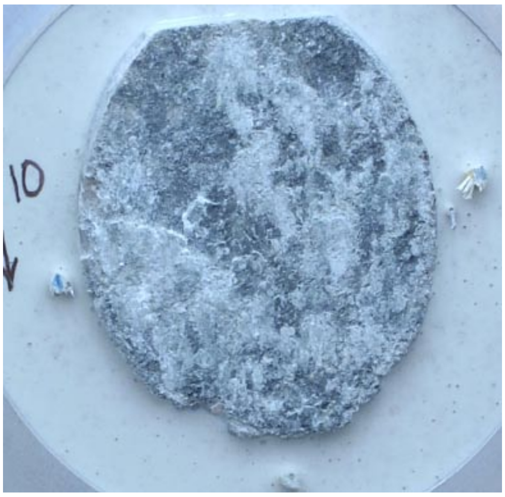
Specimen ID: KLX02-117-10

Before mechanical test



After mechanical test



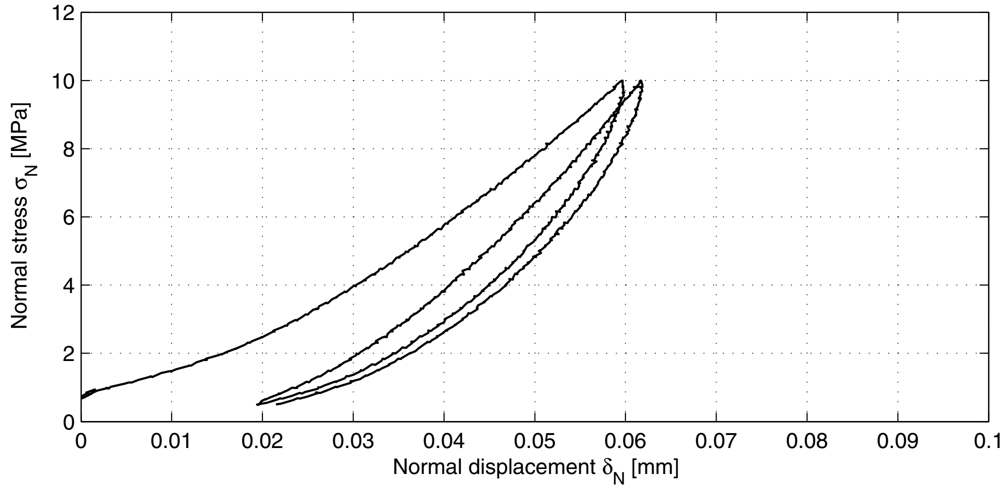


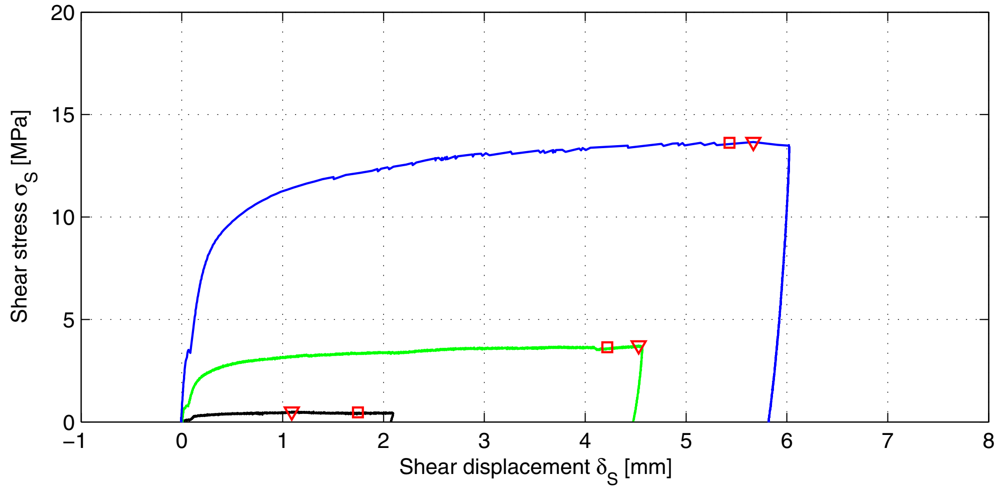
Comments

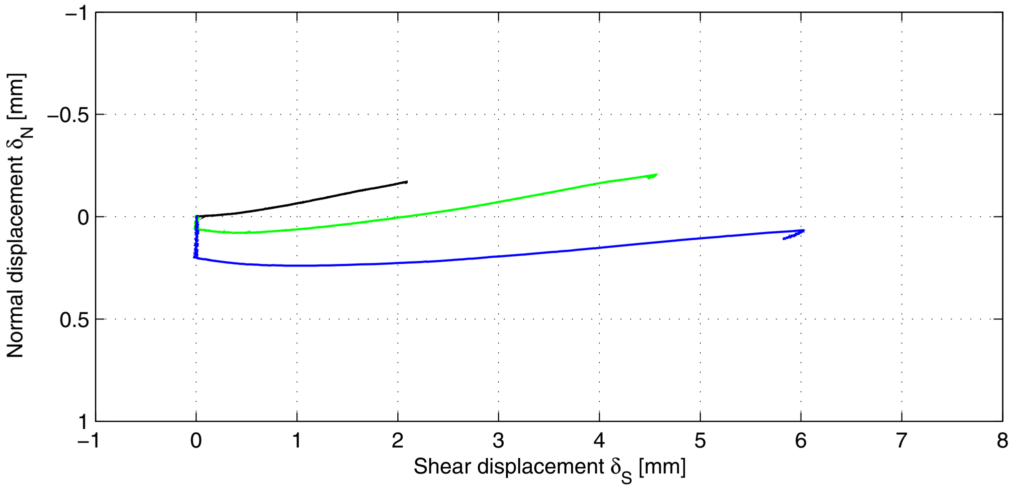
Specimen ID: KLX02−117−10

Joint area : 21.5 cm^2

Specimen height : 34.3 mm







5.2 Results for the entire test series

A summary of the test results is shown in Tables 5-1 and 5-2.

Table 5-1. Summary of results.

Identification	Area (cm^2)	Peak 05 (MPa)	Resid 05 (MPa)	Peak 5 (MPa)	Resid 5 (MPa)	Peak 20 (MPa)	Resid 20 (MPa)	Comments
KLX02-117-1	22.9	0.57	0.47	3.80	3.59	13.69	12.70	
KLX02-117-2	23.2	0.88	0.66	5.54	4.47	17.84	14.36	
KLX02-117-3	20.5	0.66	0.62	4.22	4.02	15.12	14.99	
KLX02-117-4	20.3	1.09	0.53	5.16	3.61	16.09	10.90	
KLX02-117-5	23.6	0.64	0.59	4.79	4.48	17.57	15.48	
KLX02-117-6	19.7	1.15	0.58	5.06	3.05	15.79	12.18	
KLX02-117-8	25.9	0.90	0.63	5.79	3.86	17.51	14.24	
KLX02-117-9	24.8	0.99	0.58	5.46	4.18	17.29	16.15	
KLX02-117-10	21.5	0.51	0.46	3.73	3.64	13.66	13.62	

Table 5-2. Calculated mean values and standard deviation (Std dev).

	Peak 05 (MPa)	Resid 05 (MPa)	Peak 5 (MPa)	Resid 5 (MPa)	Peak 20 (MPa)	Resid 20 (MPa)
Mean value (all specimens)	0.82	0.57	4.84	3.88	16.06	13.85
Mean value (316–317 m)	0.70	0.58	4.52	4.03	15.55	14.02
Mean value (489–501 m)	0.96	0.57	5.00	3.71	16.48	12.85
Mean value (735–740 m)	0.80	0.56	4.99	3.89	16.16	14.67
Std dev (all specimens)	0.24	0.07	0.76	0.46	1.64	1.68
Std dev (316–317 m)	0.16	0.10	0.90	0.44	2.11	1.19
Std dev (489–501 m)	0.28	0.03	0.19	0.72	0.95	2.37
Std dev (735–740 m)	0.26	0.09	1.11	0.27	2.16	1.32

5.3 Discussion

The testing was conducted according to the method description and the activity plan with no departures.

References

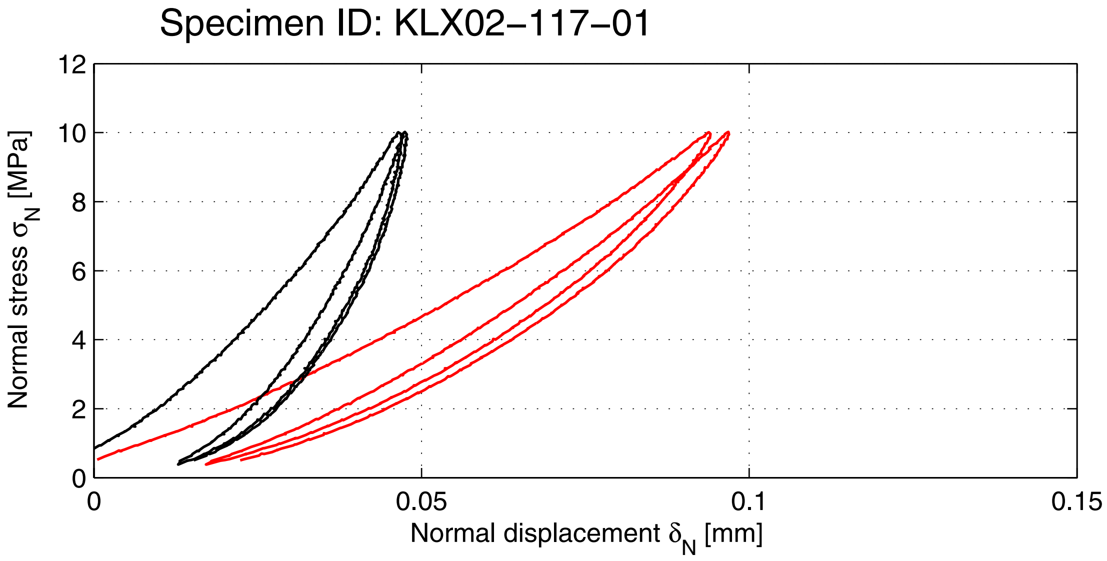
/1/ **ISRM, 1974.** Suggested methods for determining shear strength. Part 2: Suggested method for laboratory determination of direct shear strength. Final draft 1974.

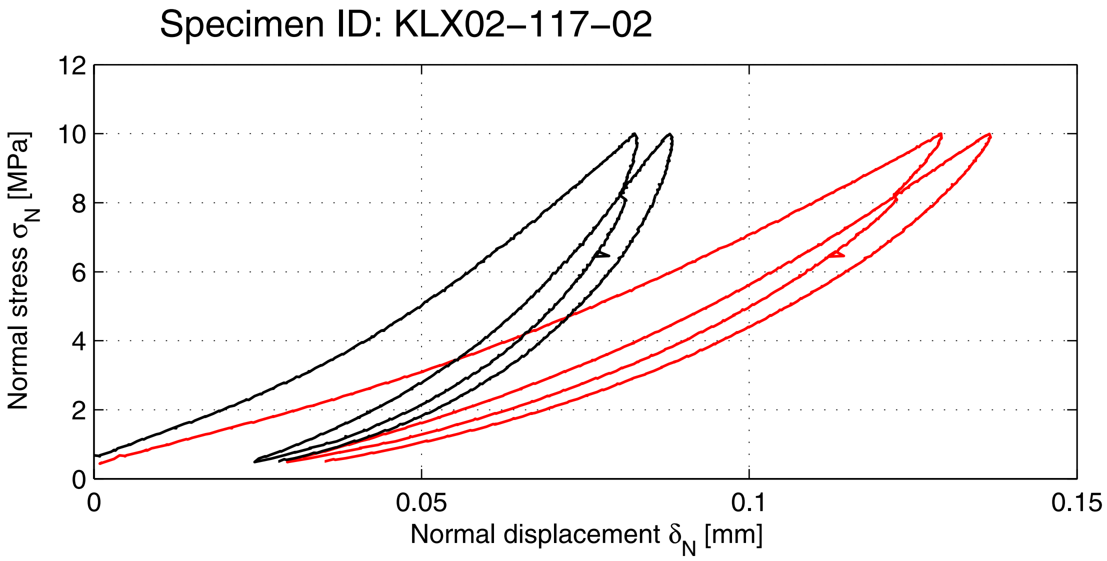
/2/ **Stråhle A, 2001.** Definition och beskrivning av parametrar för geologisk, geofysisk och bergmekanisk kartering av berg. SKB-01-19. In Swedish. Svensk Kärnbränslehantering AB.

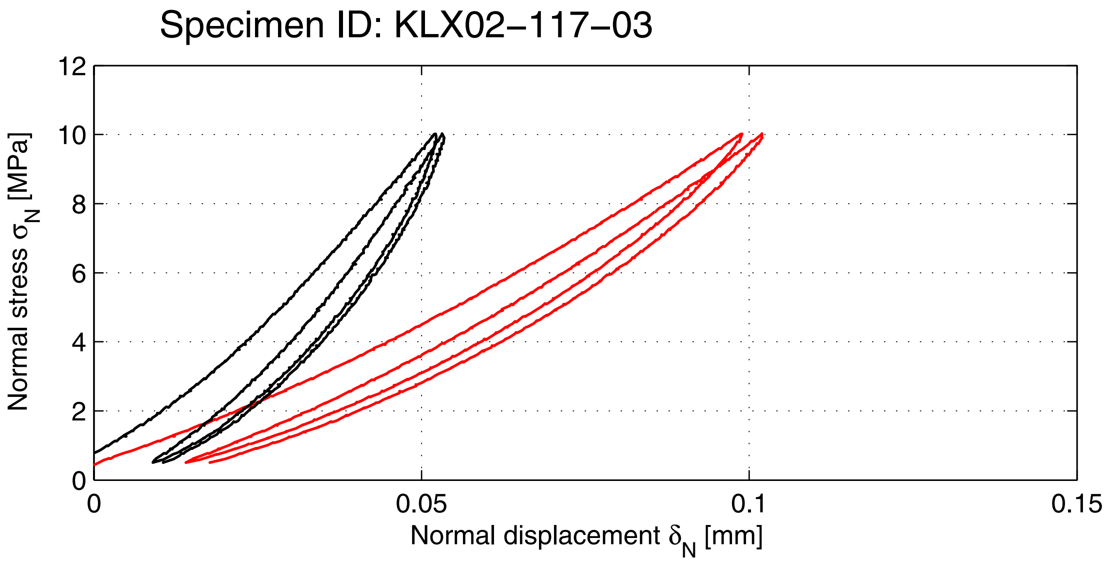
/3/ **MATLAB, 2002.** The Language of Technical computing, Version 6.5, MathWorks Inc.

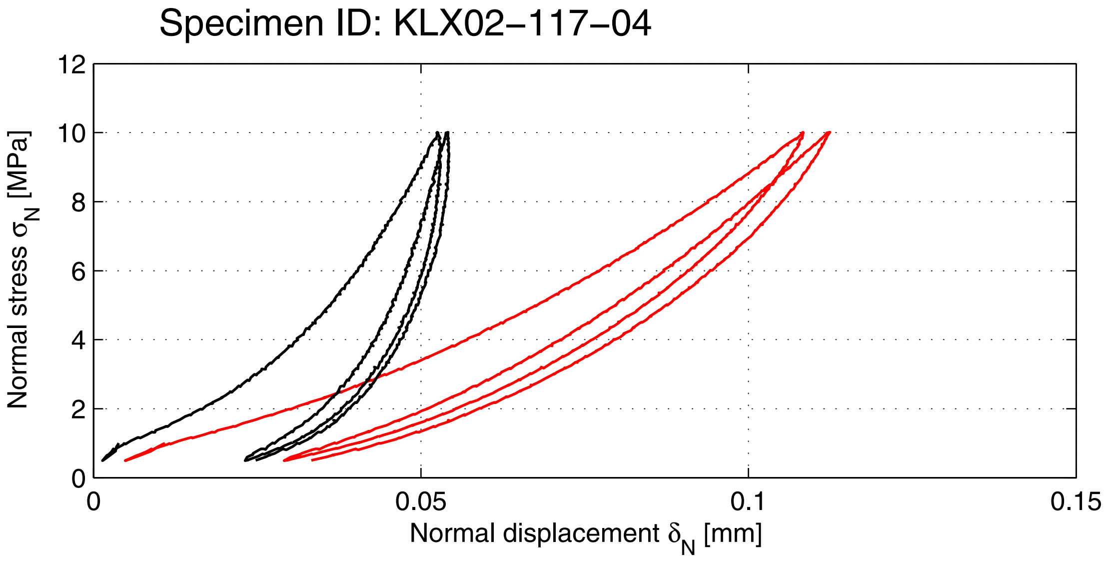
Appendix A

Results from the normal loading tests are shown below. The original unprocessed results (red) and results where the normal deformation from the system has been subtracted from the measured total normal deformation (black) are displayed in the diagrams.

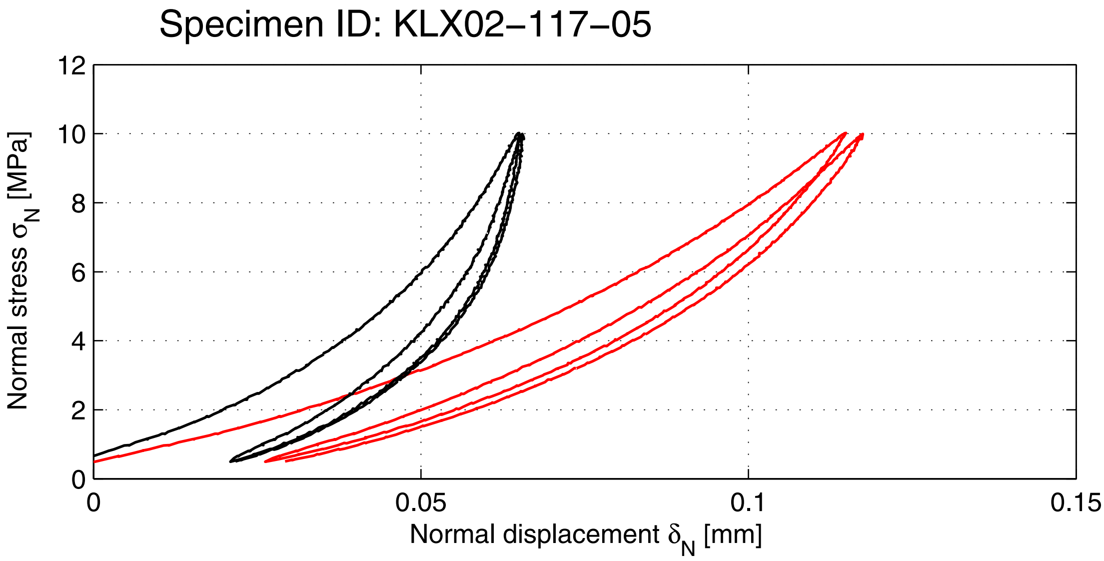

Specimen ID: KLX02–117–01
Normal stress σ_N [MPa]
Normal displacement δ_N [mm]


Specimen ID: KLX02–117–02
Normal stress σ_N [MPa]
Normal displacement δ_N [mm]

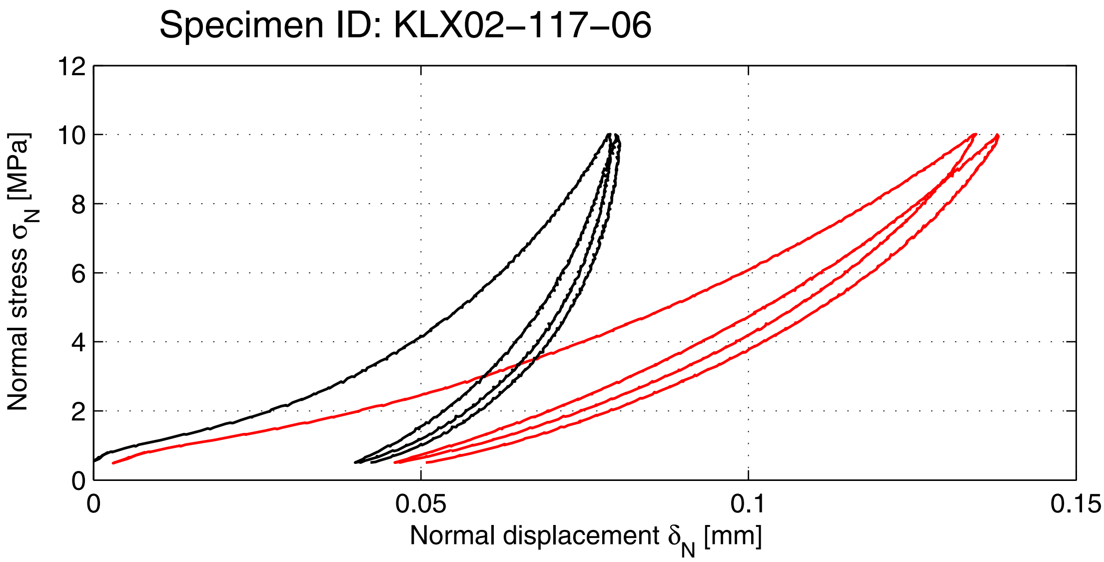

Specimen ID: KLX02–117–03
Normal stress σ_N [MPa]
Normal displacement δ_N [mm]



Specimen ID: KLX02−117−04
Normal stress σN [MPa]
Normal displacement δN [mm]
0
2
4
6
8
10
12
0
0.05
0.1
0.15

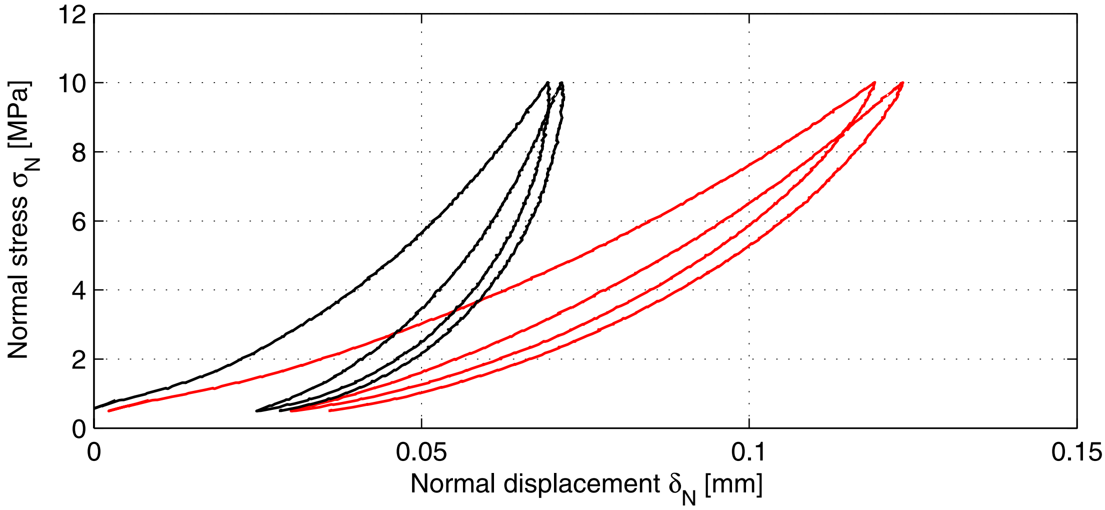


Specimen ID: KLX02−117−05
Normal stress σN [MPa]
Normal displacement δN [mm]
0
2
4
6
8
10
12
0
0.05
0.1
0.15

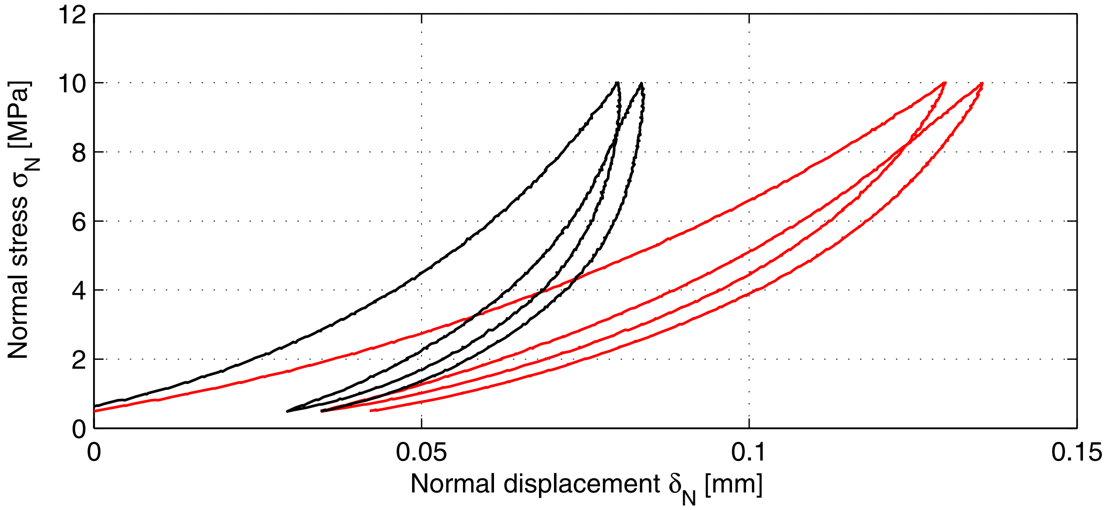


Specimen ID: KLX02−117−06
Normal stress σN [MPa]
Normal displacement δN [mm]
0
2
4
6
8
10
12
0
0.05
0.1
0.15

Specimen ID: KLX02–117–08



Specimen ID: KLX02–117–09



Specimen ID: KLX02–117–10