P-05-122

Forsmark site investigation

Borehole KFM06A

Normal loading and shear tests on joints

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August 2005

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Abstract

Normal loading tests and shear tests on joints on 6 rock specimens from borehole KFM06A in Forsmark have been carried out. The specimens were taken from cores of medium-grained granite at a depth level ranging between 395–494 m borehole length.

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 values for the peak shear stress and the residual stress were 0.80 MPa and 0.50 MPa respectively for the 0.5 MPa normal stress level, 4.62 MPa and 3.83 MPa respectively for the 5 MPa normal stress level, and 15.17 MPa and 13.78 MPa respectively for the 20 MPa stress level.

Sammanfattning

Normalbelastnings- och skjuvförsök har genomförts på 6 stycken naturliga sprickor i bergprov från borrhål KFM06A i Forsmark. Proven har tagits från borrkärnor vid en djupnivå mellan 395–494 m borrhålslängd och bestod av medelkornig 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 0,80 MPa och 0,50 MPa med 0,5 MPa normalspänning, 4,62 MPa och 3,83 MPa med 5 MPa normalspänning och 15,17 MPa och 13,78 MPa med 20 MPa normalspänning.

Contents

1 Introduction

Normal loading and shear tests on joints have been conducted on specimens sampled from borehole KFM06A in Forsmark, see map in Figure 1-1. These tests belong to one of the activities performed as part of the site investigation in the Forsmark area managed 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 Swedish National Testing and Research Institute (SP). All work was performed in accordance with the activity plan AP PF 400-04-121 (SKB internal controlling document) and is controlled by SP-QD 13.1 (SP internal quality document).

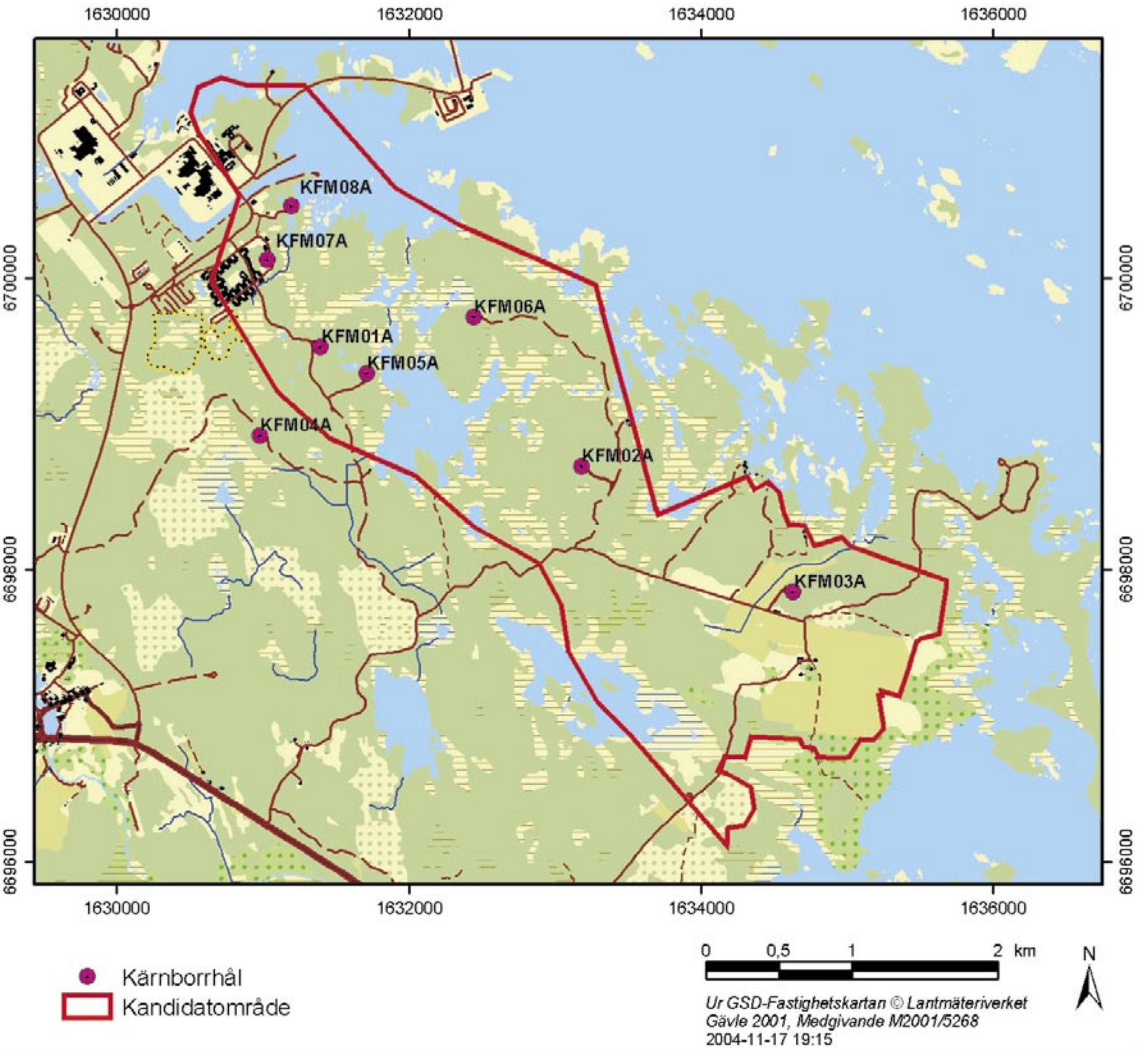


Figure 1-1. *Location of the borehole KFM06A at the Forsmark site.*

SKB supplied SP with rock cores, which arrived at SP in February 2005 and were tested during May 2005. 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 of joints of the dominant rock types.

The mechanical testing is divided into two different tests, the normal loading test and the shear test. Two normal loading cycles with a loading between 0.5 MPa and 10 MPa were carried out in the normal loading tests. A direct measurement of the joint displacement is obtained by use of crack opening displacement gauges (COD). In the shear tests, three successive shear cycles were conducted with a constant normal stress, at 0.5, 5 and 20 MPa, respectively. The shear deformation was controlled and given a constant deformation rate, and the shear stress and the normal deformation of 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.

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 of the joints during shearing at different constant normal stress levels were obtained from the shear tests. The results from the tests are to be used in site descriptive the rock mechanics model, which will be established for the candidate area selected for site investigations at Forsmark.

The specimens are collected from borehole KFM06A, a telescopic borehole which is inclined c 60° from the horizontal plane and with a drilling length of c 1,000 m. Drill cores were produced within the interval c 100–1,000 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.

Before each of the normal loading tests and the shear test, 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 applied 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.

For the normal loading test the specimens were cast in fast setting cement. The thickness of the cement layer was chosen to be as thin as possible to obtain a stiff support, at the same time as the stress was allowed to be evenly distributed to avoid cracking of the rock specimen.

For the shear test, 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.

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 employed for the normal loading and shear tests, see Figure 3-1. The machine is supplied with two shear boxes, one upper and one lower. The upper box can be moved vertically and the lower 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 guidance of the lower box in order to have a controlled linear movement. The maximum stroke is 100 mm in the vertical direction and +/– 50 mm in the shear direction.

In the normal loading test the normal displacement over the joint is measured by the use of two crack opening displacement gauges (COD) attached at two opposite sides of the rock specimen. Each of the CODs has a measurement range of 4 mm and a relative error less than 1%. The average value of these two CODs is used to represent the normal deformation over the rock joint presented in the results section.

In the shear test 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 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 mechanical testing is divided into two separate tests, the normal loading test and the shear test. The 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/.

For each specimen, a form is filled in containing specimen dimensions. Further, the form also contains comments and observations during the different test steps. Moreover, a check list is filled in during the work in order to confirm that the different specified steps have been carried out. The specimens are photographed before and after the mechanical tests.

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 (borehole length) and rock type for all specimens.

Identification	Secup (m)	Seclow (m)	Rock type
KFM06A-117-1	395.28	395.38	Medium-grained granite
KFM06A-117-2	429.67	429.84	Medium-grained granite
KFM06A-117-4	452.29	452.37	Medium-grained granite
KFM06A-117-5	452.96	453.03	Medium-grained granite
KFM06A-117-7	470.70	470.88	Medium-grained granite
KFM06A-117-8	493.48	493.58	Medium-grained 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 of approximately 30 mm and a maximum length l of 60 mm, cf Figure 4-1. The specimens will therefore have similar shape and joint area size.

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

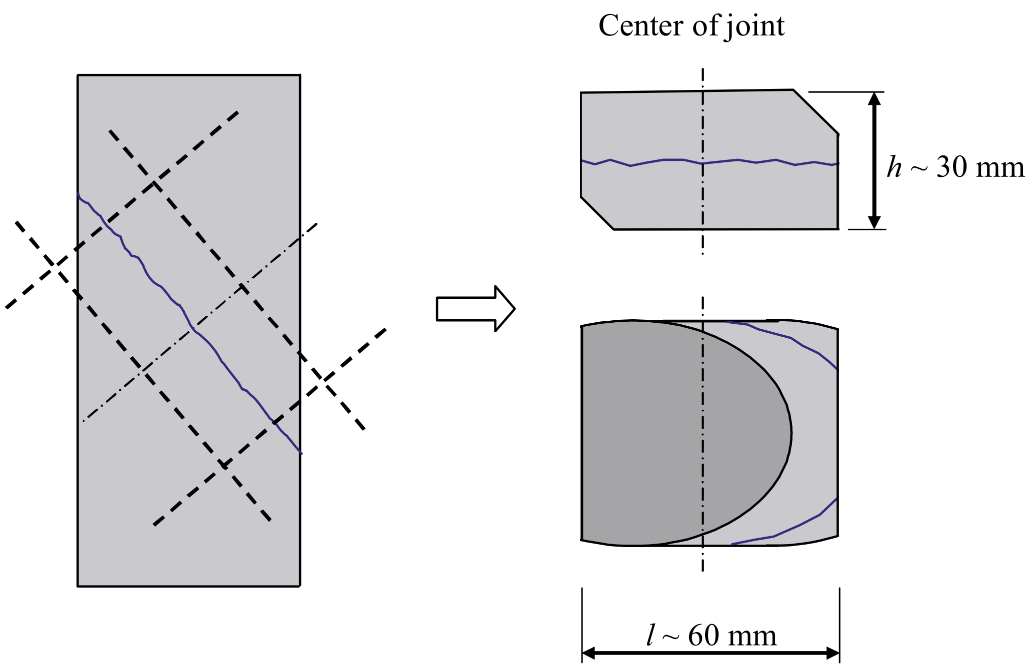


Figure 4-1. *Principle of specimen processing. Left: Cylindrical core containing a joint. The dashed lines show the cutting lines; Right: Specimen after processing.*

Table 4-2. Activities during the specimen preparation.

Step	Activity
1	Mark the drill cores at the position of the joints 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.

4.3 Mechanical testing

The mechanical testing is divided into two separate tests, the normal loading test and the shear test. The program controlling the tests includes 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.

4.3.1 Normal loading test

The specimens are grouted in steel holders, which consist of one upper and one lower half, using fast setting cement, see Figure 4-2. A direct measurement of the joint displacement is obtained by use of crack opening displacement gauges (COD) attached between two small metal pieces glued to the opposite sides of the rock joint.

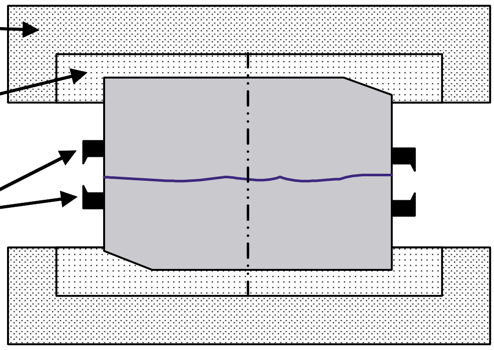


Figure 4-2. *Specimen cast with cement in the specimen holder for the normal loading tests.*

First, the two pairs of small metal pieces, to be used as holders for the COD gauges, are glued onto two opposite sides of the rock specimen. One half of the specimen is cast by pouring the cement into the holder with the specimen held in the correct position. The cement is hard enough after one hour to fixate the specimen. The second half of the specimen is positioned relative to the first one such that the two specimen pieces best fit together, implying that the joint is optimally closed. The second half of the holder is then mounted on top of the first one with a 26 mm gap between the two halves and turned upside down. The second half is cast by pouring cement into the holder. The cement is fully hardened after one day in room temperature.

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 test was conducted with a loading/unloading rate of 10 MPa/min. The normal deformation over the joint measured by the COD gauges was recorded. After the test was completed, the specimen was removed from the grout and the metal pieces were removed from the specimen.

An overview of the activities during the normal loading test is shown in the step-by-step description in Table 4-3.

Table 4-3. Activities during the normal loading test.

Step	Activity
1	Glue the metal pieces onto the specimen.
2	Cast the specimens into the specimen holders.
3	Mount the specimen holders in the shear testing machine.
4	Attach the two COD gauges.
5	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.
6	Remove the specimens from the shear boxes.
7	Remove the metal pieces and holders from the specimen.
8	Store the test results on the computer network.

4.3.2 Shear test

The specimens are cast in steel holders using an epoxy that is reinforced with fine quartz sand in order to increase the stiffness, see Figure 4-3. 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 by pouring the epoxy into the holder with the specimen held in 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 half a day up to one day, the holders with the cast specimens 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 cool down to room temperature.

Three successive 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.

An overview of the activities during the shear test is shown in the step-by-step description in Table 4-4.

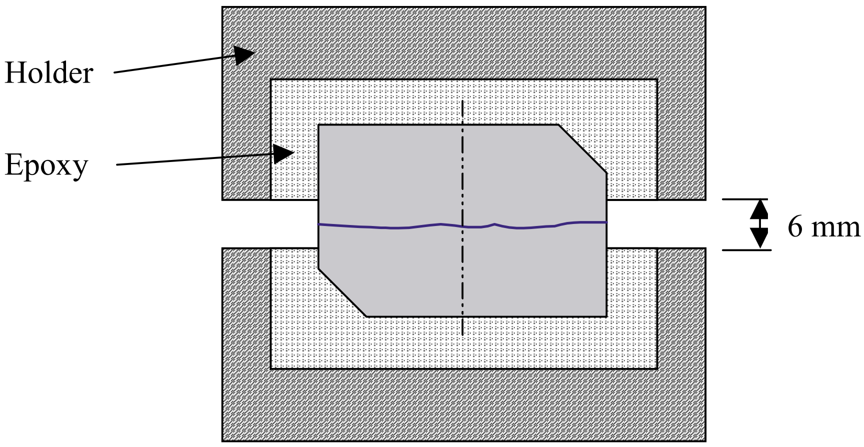


Figure 4-3. *Specimen cast in the specimen holder for the shear tests.*

Table 4-4. Activities during the shear test.

Step	Activity
1	Cast the specimens into the specimen holders.
2	Install the specimen holders in the shear testing machine.
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	Remove 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. 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

4.5.1 Normal loading test

The results of the normal loading tests with direct deformation measurement are represented by normal stress-normal deformation relations. The normal stress σ_N is defined as

$$\sigma_N = \frac{F_N}{A}$$

where F_N is the normal force acting on the joint and A is the area of the joint. In the normal loading tests the joint deformation in the normal direction, δ_N, is defined as

$$\delta_N = \frac{\delta_{COD1} + \delta_{COD2}}{2}$$

where δ_{COD1} and δ_{COD2} are the measured displacements recorded by the two COD gauges during the tests.

4.5.2 Shear test

In the shear tests, the normal stress σ_N and shear stress σ_S are defined as

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

where F_N is the normal force and F_S is the shear force acting on the joint and A is the 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 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. In some cases 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 used when the residual value is evaluated, is defined as the envelope obtained by interconnecting the sub-peaks achieved 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 new points created are determined by the criterion that the distance of the added points should be just less or equal to 0.01 mm.

The shear deformation δ_S is represented by the relative displacement between the shear boxes in the horizontal (shear) direction measured by one LVDT. The normal deformation δ_N is defined as the average value of four LVDTs used to measure the vertical (normal) displacement between the two shear boxes.

Part of the normal deformations and shear deformations measured in the shear tests are due to the deformations of the epoxy, in the holders and shear boxes and in the contact surfaces between the specimen holders and the shear boxes. However, the system deformations during the shear tests are of less significance for the results and no correction is made.

4.6 Nonconformities

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

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, where data are traceable by the activity plan number. 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.

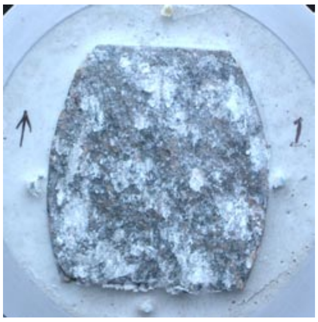
5.1 Description and presentation of the specimens

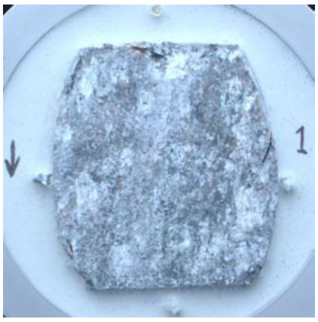
The specimens and joints before casting and after testing are shown on pictures. Comments on observations made during the testing are reported. The results from the normal loading tests are shown in the upper diagrams and the results from shear tests are presented in the middle and the lower diagrams. 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 the residual stresses. Moreover, the dilatancy in the joints is derived from the shearing part of the three shear cycles.

Specimen ID: KFM06A-117-1

Before mechanical test

After mechanical test





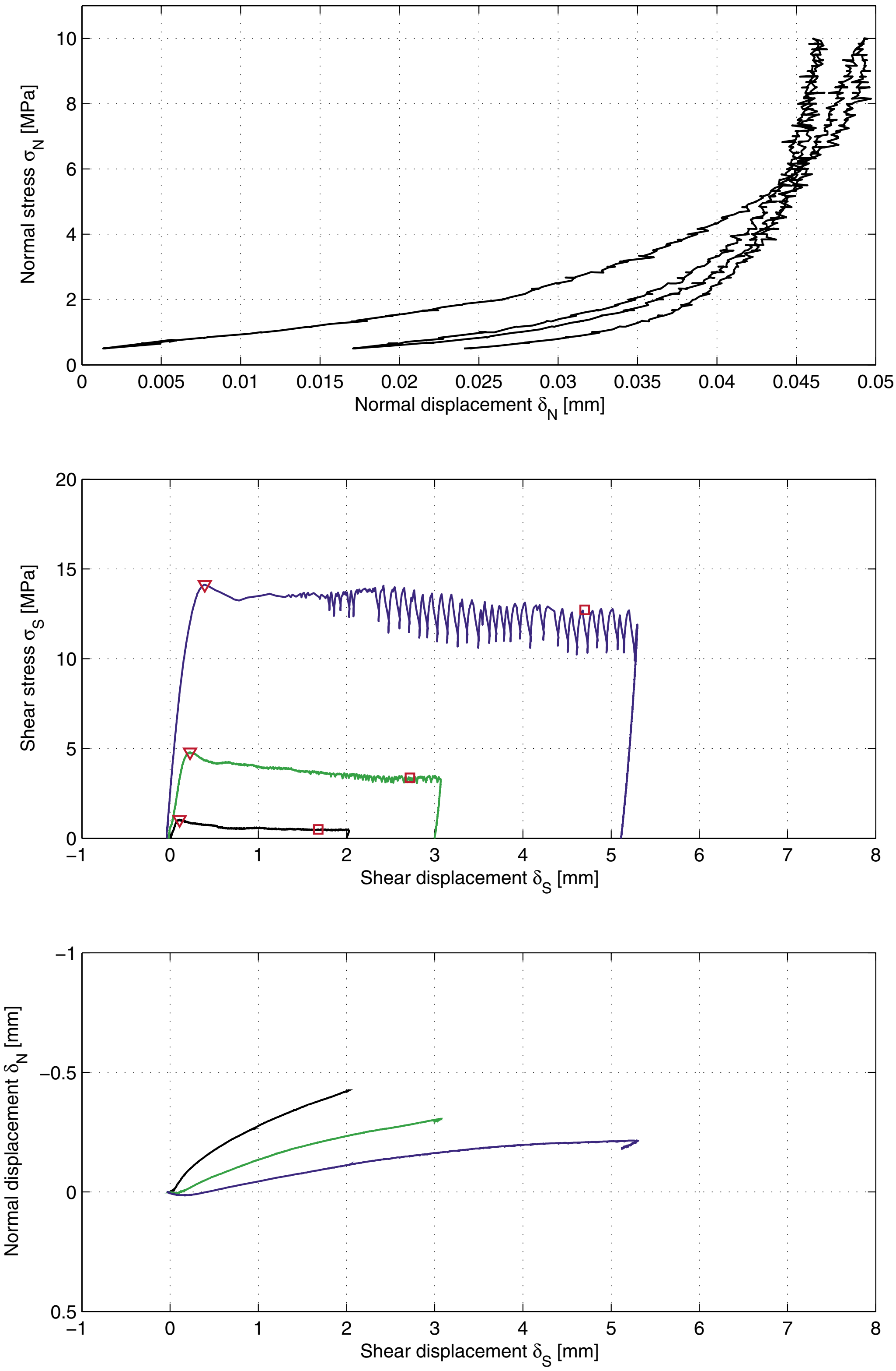
Comments Upper half: At the rear end of the specimen, small pieces have spalled off.

Lower half: At the rear end of the specimen, small pieces have spalled off.

In the results from the normal loading test it can be seen that the average normal deformation is larger in the first load cycle than in the second cycle. A comparison of the results of the individual COD gauges shows uneven settlements which indicate a small relative rotation between the two halves during the consolidation in the first load cycle. However, in the second load cycle the difference in relative deformation between the two gauges is small.

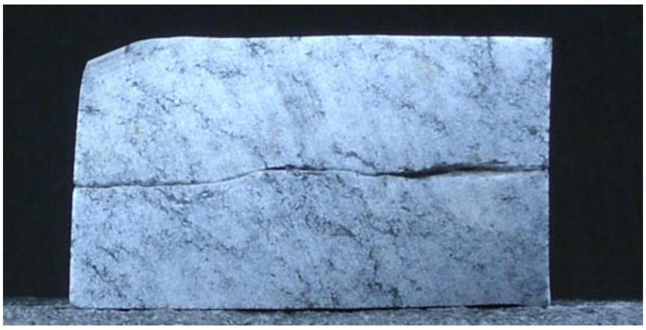
Specimen ID: KFM06A−117−01

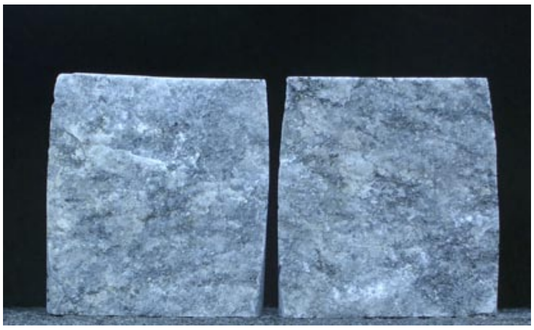
Joint area : 25.4 cm^2



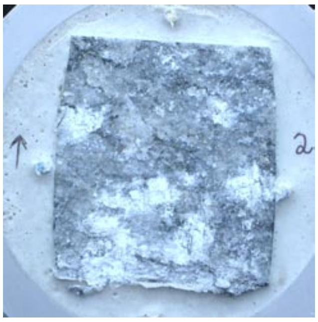
Specimen ID: KFM06A-117-2

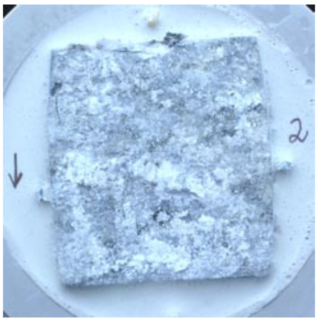
Before mechanical test





After mechanical test



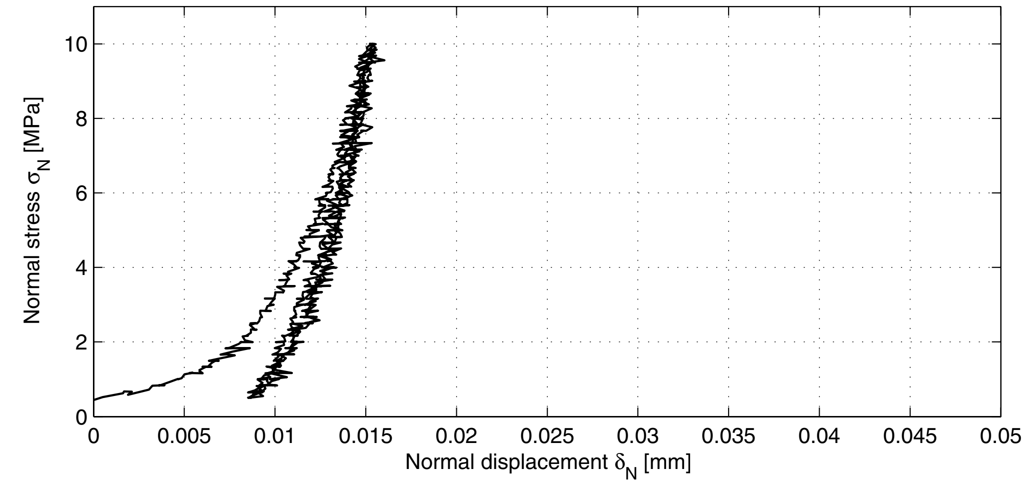


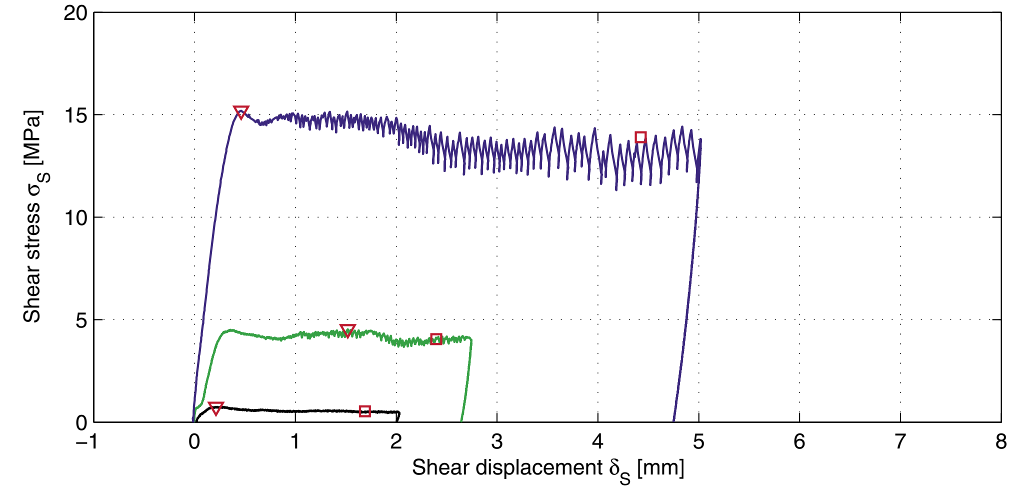
Comments Upper half: At the rear end of the specimen, small pieces have spalled off.

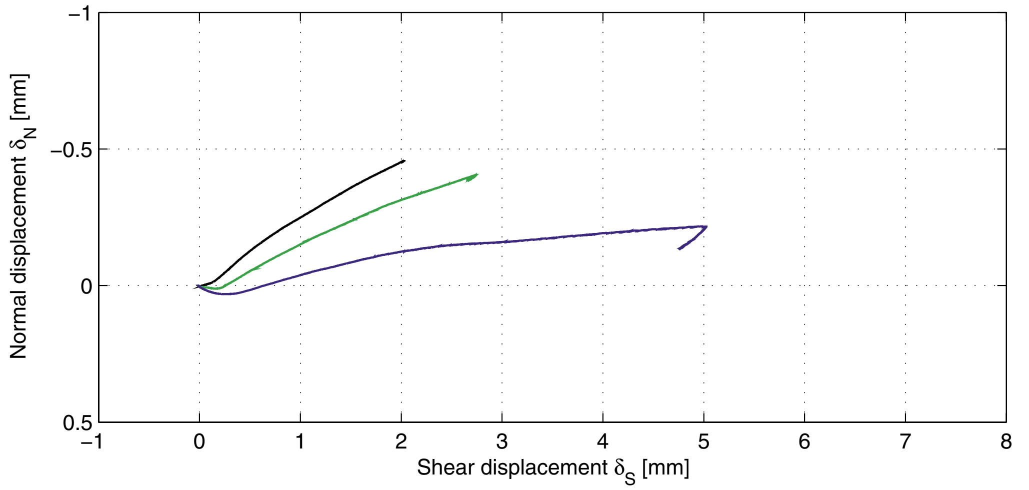
Lower half: At the rear end of the specimen, small pieces have spalled off.

Specimen ID: KFM06A−117−02

Joint area : 27.1 cm^2



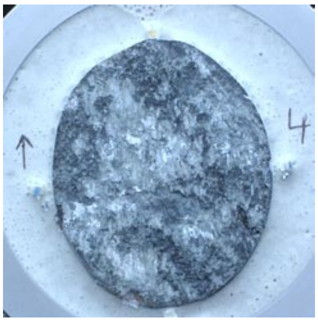


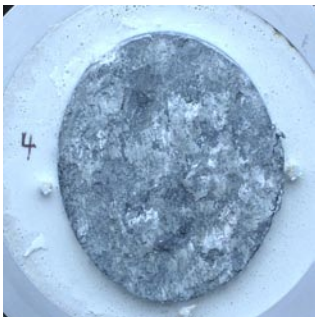


Specimen ID: KFM06A-117-4

Before mechanical test

After mechanical test

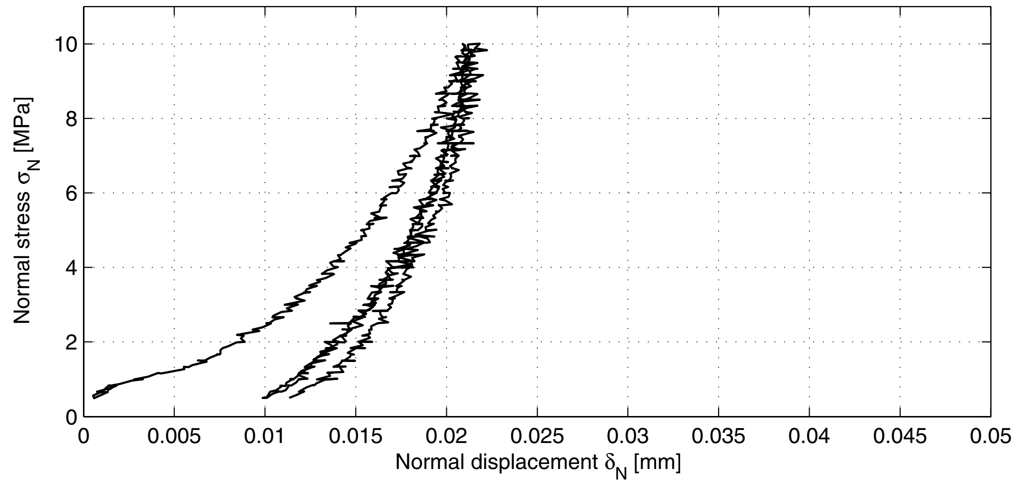


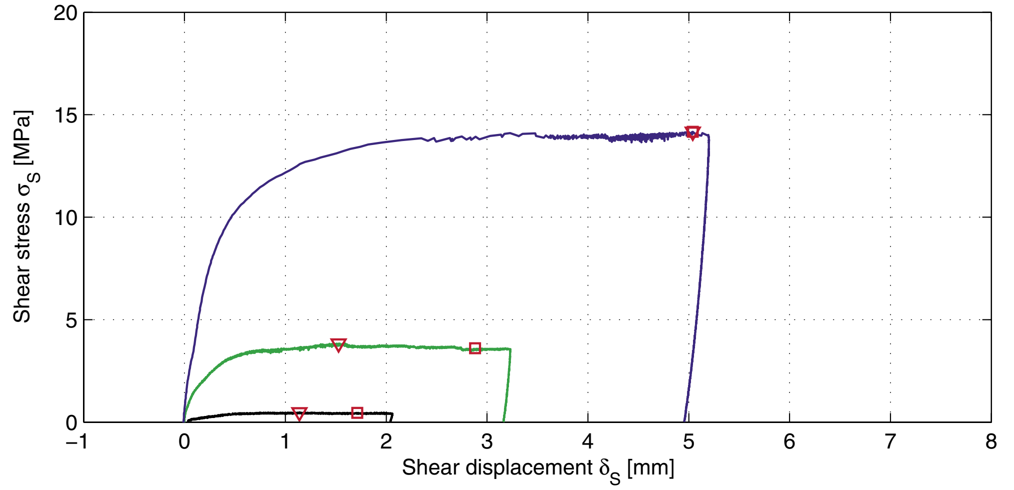


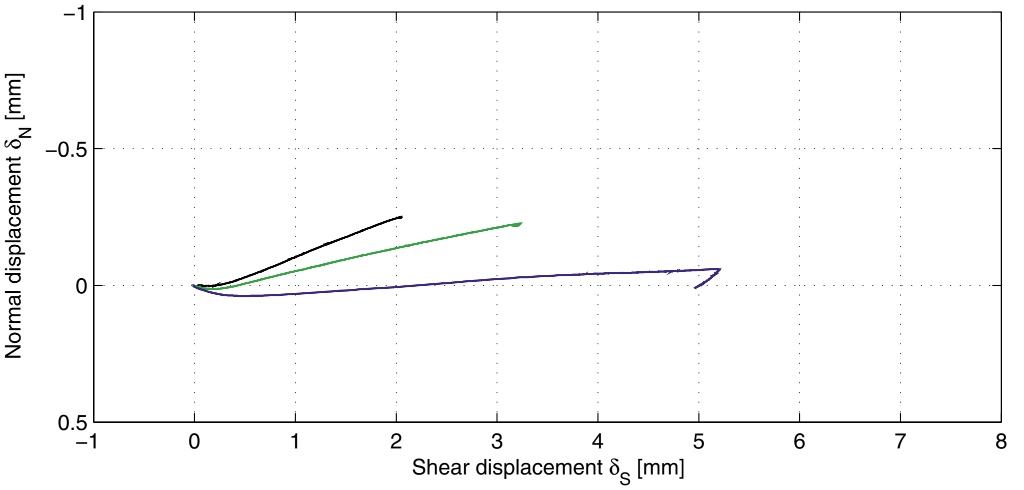
Comments The residual shear stress can not be distinguished from the peak shear stress at the 20 MPa normal stress level.

Specimen ID: KFM06A−117−04

Joint area : 23.9 cm^2



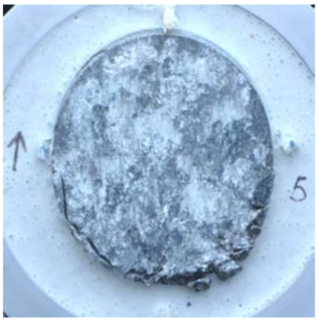




Specimen ID: KFM06A-117-5

Before mechanical test

After mechanical test

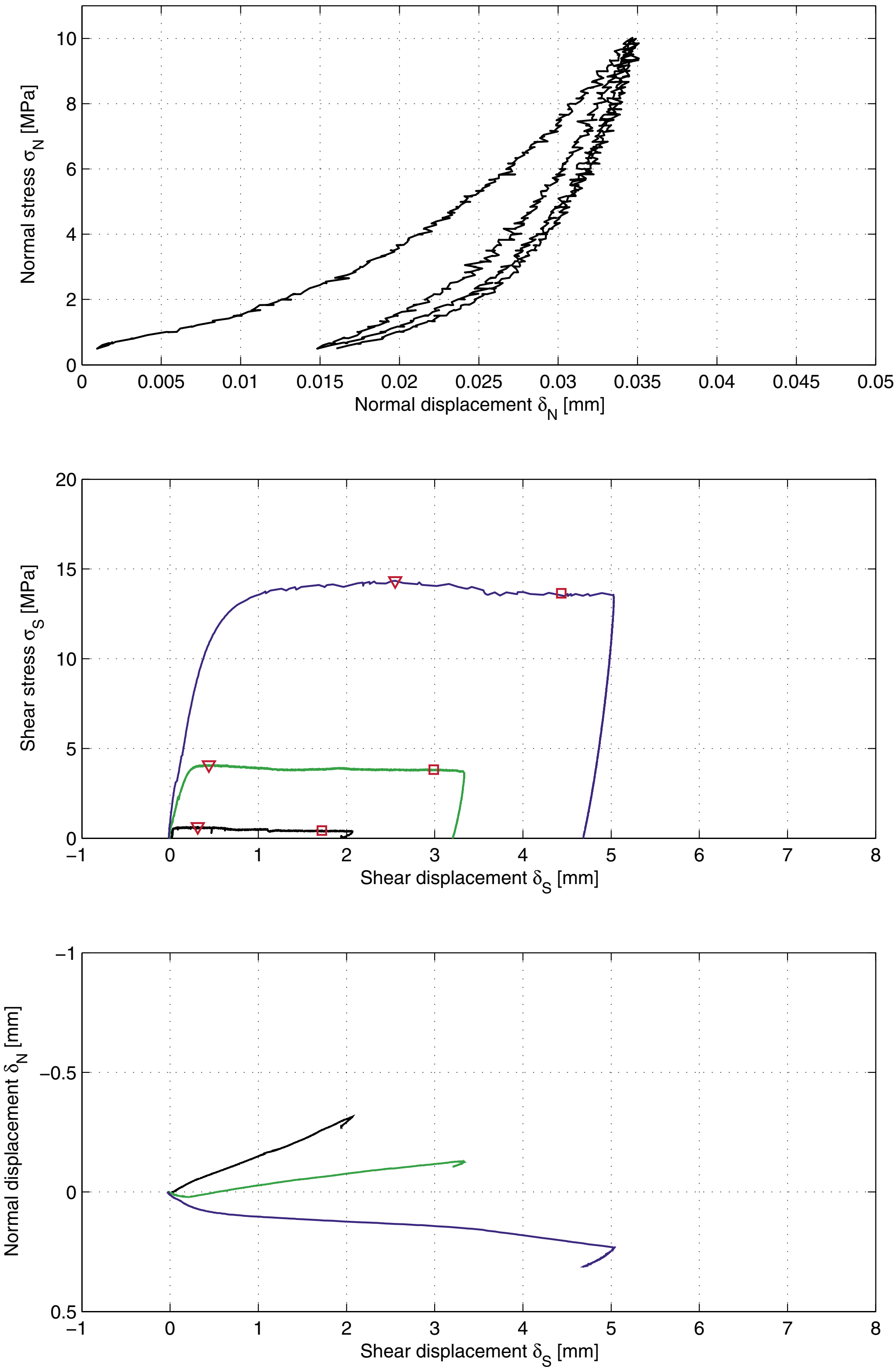



Comments Upper half: At the rear end of the specimen, pieces have spalled off.

Lower half: At the rear end of the specimen, small pieces have spalled off.

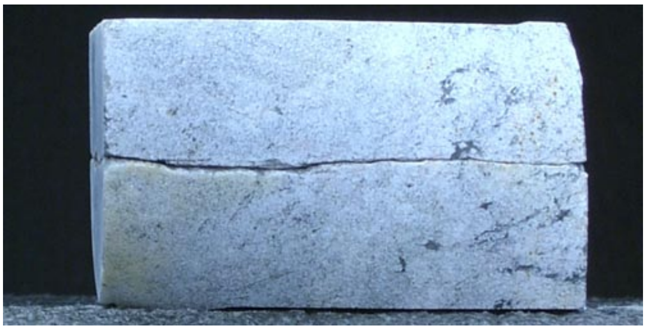
Specimen ID: KFM06A–117–05

Joint area : 22.5 cm^2

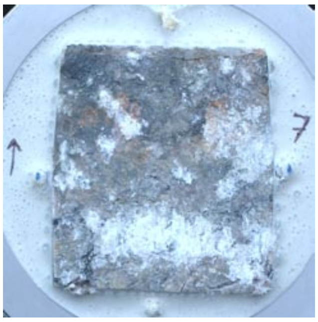


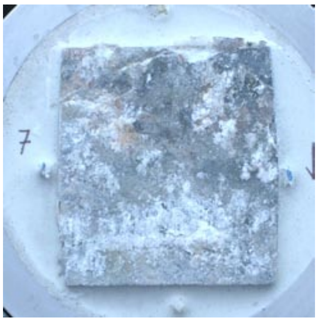
Specimen ID: KFM06A-117-7

Before mechanical test



After mechanical test



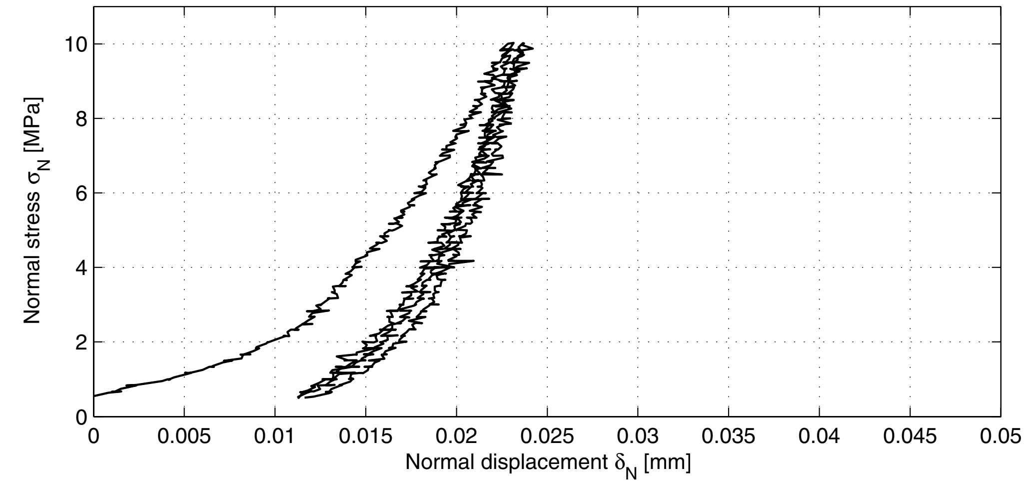


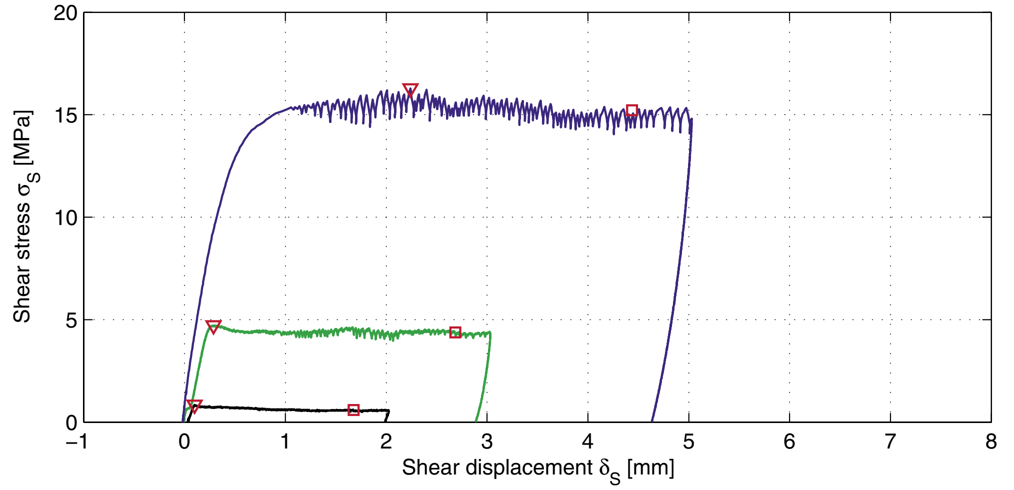
Comments Upper half: At the rear end of the specimen, small pieces have spalled off.

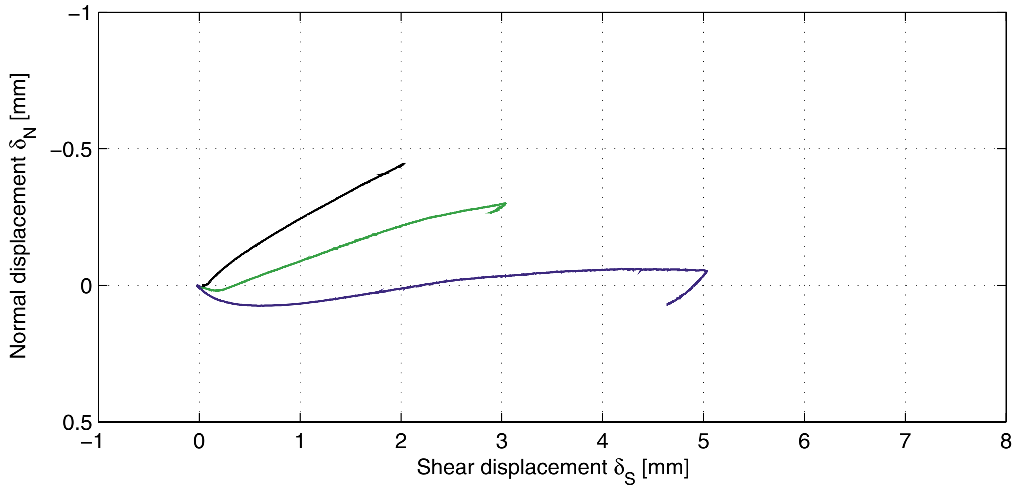
Lower half: At the rear end of the specimen, small pieces have spalled off.

Specimen ID: KFM06A−117−07

Joint area : 27.1 cm^2



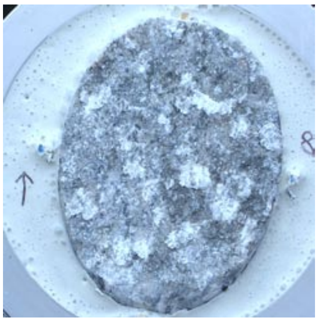


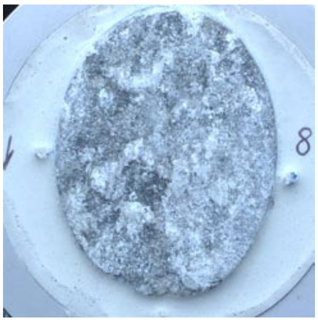


Specimen ID: KFM06A-117-8

Before mechanical test

After mechanical test

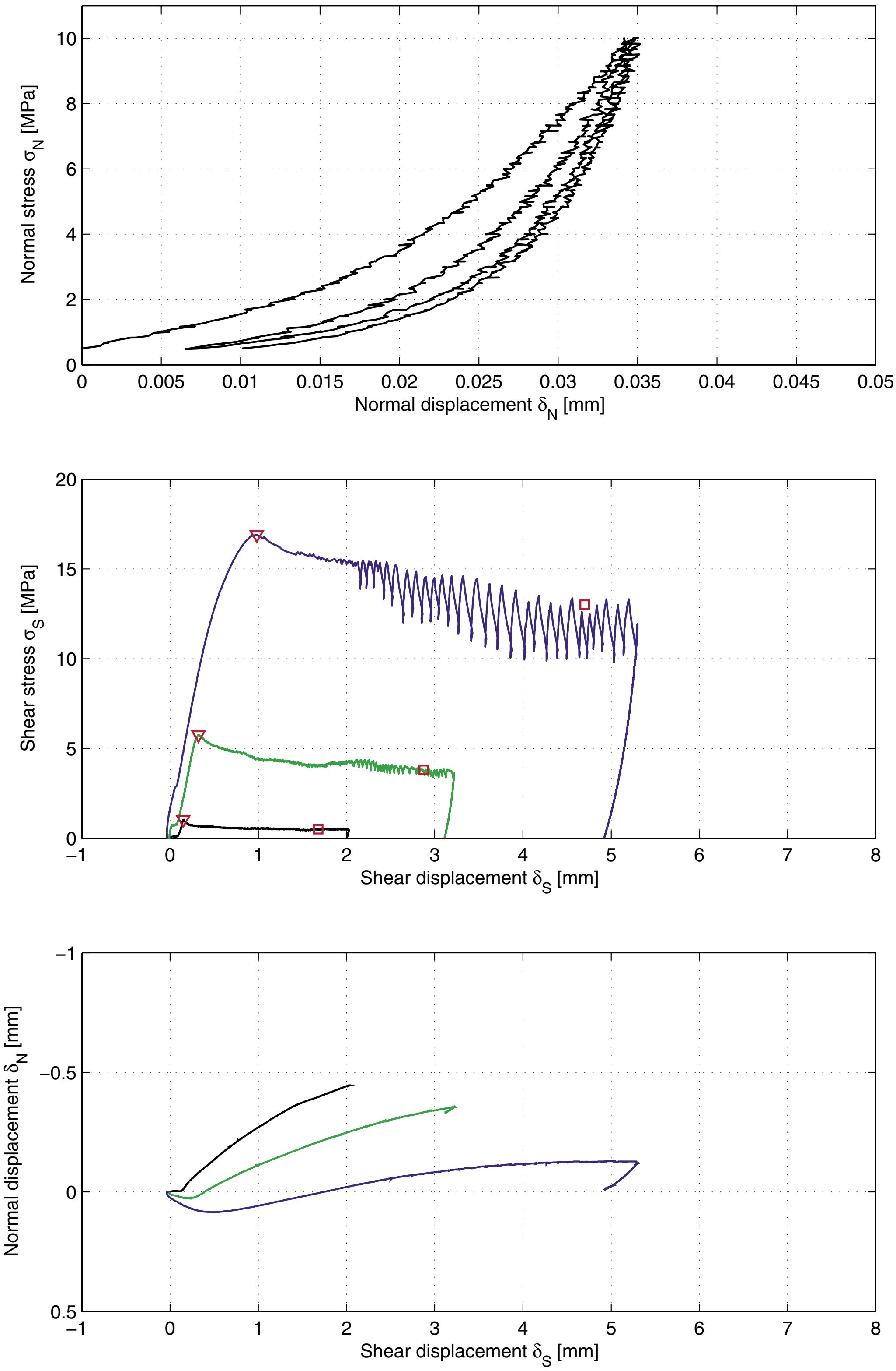




Comments

Specimen ID: KFM06A−117−08

Joint area : 25.8 cm^2



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
KFM06A-117-1	25.4	1.04	0.49	4.79	3.36	14.13	12.72	
KFM06A-117-2	27.1	0.75	0.53	4.53	4.05	15.20	13.90	
KFM06A-117-4	23.9	0.47	0.45	3.84	3.60	14.16	14.16	
KFM06A-117-5	22.5	0.64	0.42	4.09	3.82	14.35	13.65	
KFM06A-117-7	27.1	0.84	0.59	4.72	4.38	16.29	15.22	
KFM06A-117-8	25.8	1.04	0.50	5.75	3.80	16.90	13.02	

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)	0.80	0.50	4.62	3.83	15.17	13.78
Std dev (all specimens)	0.22	0.06	0.67	0.35	1.18	0.89

References

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

/2/ **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.

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