P-04-175

Forsmark site investigation

Drill hole: KFM01A

The normal stress and shear tests on joints

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May 2004

Reviewed by Toralv Berre

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Keywords: AP PF 400-04-05, Field note no Forsmark 96, Rock mechanics, Joint test, Normal and shear behaviour, Normal and shear displacement, Peak shear stress, Residual shear stress.

Abstract

On behalf of the Swedish Nuclear Fuel & Waste Management Co (SKB), the Norwegian Geotechnical Institute (NGI) has carried out five direct shear tests on joints on rock samples from borehole KFM01A, Forsmark, Sweden. The main objective of this study has been to compare these results with the results of similar tests performed by the Swedish National Testing and Research Institute (SP), in Borås Sweden.

The tested specimens were of fine-grained granodiorite. They were specially prepared in a hard epoxy mix in order to fit the direct shear apparatus at NGI, which can take specimens up to 80 mm in diameter and 55 mm in height. The specimens were tested with shear displacements that varied from 3 to 9 mm and subjected to three normal stress levels: 0.5, 5.0 and 20.0 MPa. All specimens were tested at natural dry conditions at room temperature (i.e. at about 19°C) and according to ISRM standards /1981/ for direct shear testing.

The mean value of the peak shear stress obtained is 1.66 MPa for the normal stress level of 0.5 MPa, 4.86 MPa for the normal stress level of 5.0 MPa and 16.39 MPa for the normal stress level of 20 MPa.

Contents

1 Introduction

This document reports the data collected by direct shear tests on joints on rock samples from borehole KFM01A at Forsmark, Sweden. It is one of the activities performed as part of the on-going site investigation. The work was carried out in accordance with activity plan AP PF 400-04-05 (SKB internal controlling document) and method description MD 1900.005e, version 1.9 (SKB internal controlling document).

Specimens from borehole KFM01A, see Figure 1-1, were taken from the Forsmark site on February 24, 2003, by SKB and the Swedish National Testing and Research Institute (SP). The field note number in SKB's database is Forsmark 96. The specimens were taken from three levels of the rock core: level 1 about 230 m, level 2 about 390 m and level 3 about 700 m (all levels refer to borehole length).

The rock cores were transported by SP from Forsmark and arrived at SP on Febuary 25, 2003. The cores were marked and cut at the SP laboratory. Six specimens (joints) were sent to NGI for direct shear testing, on February 2, 2004. The specimens were tested in accordance with ISRM standards /1981/ for direct shear testing.

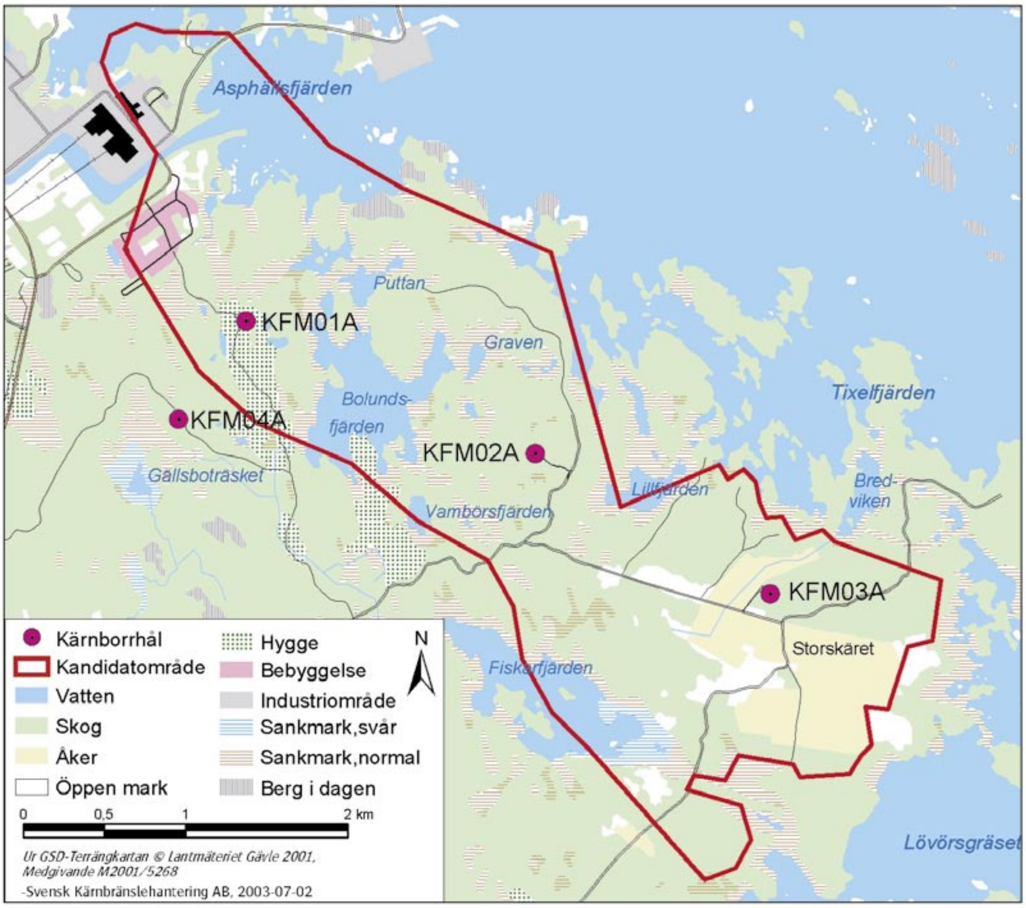

Figure 1-1. *Map of the investigation site.*

All tests were performed at the rock mechanics laboratory of the Norwegian Geotechnical Institute (NGI), during March 2004, by Panayiotis Chryssanthakis with Toralv Berre as responsible for the calibration of the equipment and the quality assurance of the performed work. Technical personnel that participated in different stages of the direct shear tests were Pawel Jankowski, Sven Vanbæk and James Oloka.

2 Objective and scope

The main objective of this experimental work is to compare the direct shear test results with results of similar tests performed at the main laboratory, the SP in Borås, Sweden.

The nature of direct shear tests on natural fractures is such, that there do not exist two exactly identical specimens. Each specimen is unique. This means that comparison of the results with other laboratories should be in terms of tendency lines. The choice of test specimens has been ruled by the two following prerequisites:

- The comparison of test results is limited to the dominating rock types in borehole KFM01A and the most representative out of these again.
- The testing is concentrated at a representative depth and several normal stress levels are applied on each test specimen.

The results are also used in the rock mechanical model, which will be established for the candidate area selected for site investigations at Forsmark.

3 Equipment

The direct shear test apparatus (DST), see Figure 3-1, for high stresses was designed and built at NGI in cooperation with the department of Geology, University of Oslo, for testing un-cemented sands at high stresses /Kjeldstad et al. 2003/. A soil or rock specimen to be tested in this apparatus can have diameter up to 80 mm (i.e. a cross section area of 50 cm^2) and a thickness up to about 55 mm. Drainage can take place through filter disks at the top and bottom of the specimen, and P and S-wave velocities can be measured. The following loads can be applied to the specimen through actuators fixed to the reaction frame and driven by electronically controlled hydraulic pumps:

Maximum vertical load = 275 kN,

Maximum horizontal load = 184 kN.

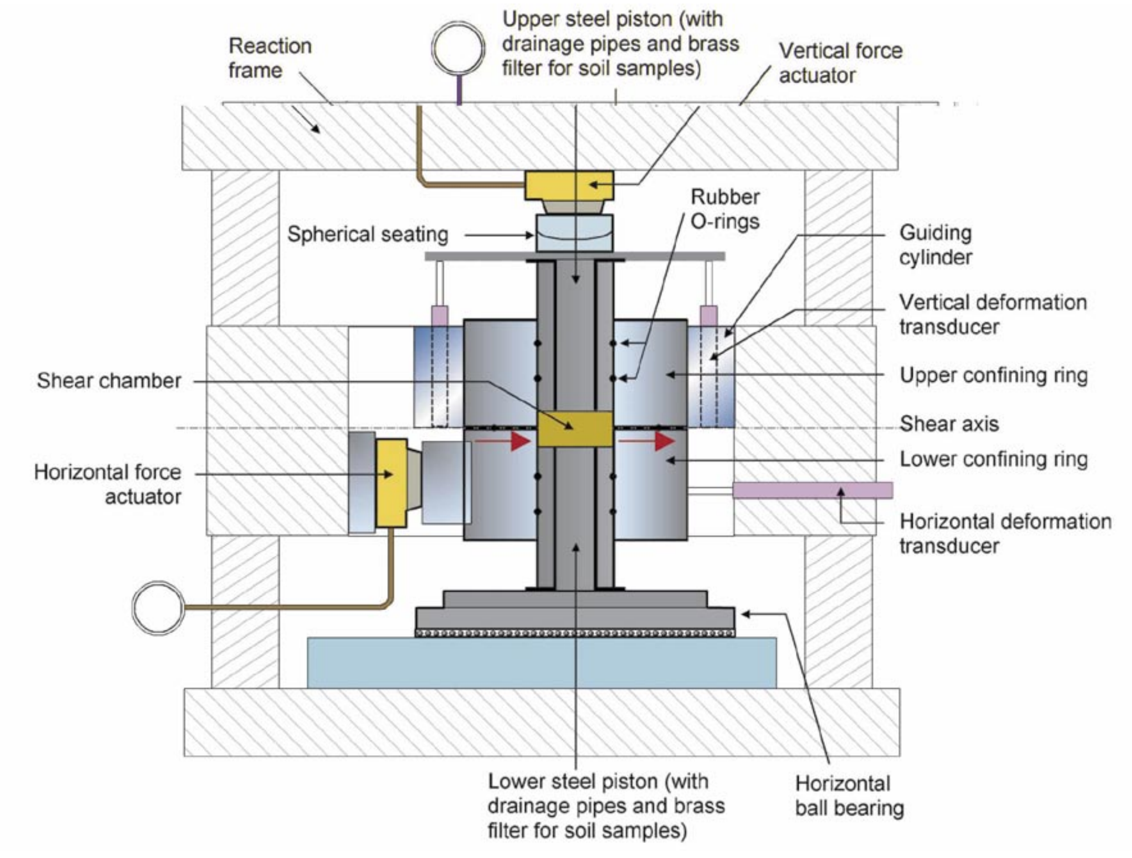

Figure 3-1. *Principle sketch showing a vertical cross-section through the NGI direct shear test apparatures (DST) for high stresses. Rock sample details show how the rock sample is mounted in epoxy and metal rings before it is placed in the shear chamber. The diameter of the chamber is 80 mm. Maximum vertical and horizontal loads that can be applied to the rock sample are 275 and 184 kN respectively. Maximum shear displacement is about 9 mm.*

The maximum travels (strokes) of the vertical and the horizontal actuators are 16 and 11 mm, respectively. The filter disk at the top and at the bottom are fixed to an upper and a lower piston, respectively. These pistons slide inside an upper and a lower confining ring. The two confining rings meet each other at middle height of the specimen and shearing takes place by moving (by the horizontal actuator) the lower confining ring horizontally while the upper confining ring is held back by a guiding cylinder fixed to the reaction frame (see Figure 3-1). Thus shearing takes place in the plane between the upper and the lower confining rings. The lower piston, which follows the lower confining ring during shearing, rests against a horizontal ball bearing which allows the horizontal movement of the lower piston during the shearing. The limitation of the vertical load (275 kN) is the maximum vertical load that can be applied to this bearing. Vertical and horizontal deformations (i.e. shear deformations) of the specimen are measured by electronic sensors (LVDT s). The vertical deformation sensors are mounted to a bracket, which is fixed to the lower steel piston (this bracket is not shown in Figure 3-1). The horizontal deformation sensor is fixed to the reaction frame.

4 Execution

The work was carried out in accordance with activity plan AP PF 400-04-05 (SKB internal controlling document) and method description MD 1900.005e, version 1.9 (SKB internal controlling document).

Rock specimens are normally tested as follows:

1) The rock specimen is cast in epoxy inside two metal rings with the same outer diameter as the inner diameter of the confining rings (see Figure 4-1). For square specimens, the side length is limited to about 50 mm. At the middle height of the specimen, there is a gap in the epoxy typically about 5 mm high where shearing of the specimen can take place. The epoxy covers both top and bottom of the specimen so that drainage from the specimen only can take place through the mid-height gap. The SKB specimens were tested in dry condition and no drainage was needed. The whole set-up (including metal rings, epoxy and rock specimen) is placed in the compartment where normally the soil specimen, but in this case the rock specimen, is placed for soil testing.

2) If very large horizontal deformations are imposed, a Teflon ring of the same thickness as the height of the gap around the rock specimen may be placed between the upper and the lower confining rings to secure that they do not get stuck in the rock specimens at large deformations. To achieve this, the inner diameter of the Teflon ring must be larger than the inner diameter of the confining rings (see Figure 3-1). (The Teflon ring was not needed for the SKB tests).

The deformation sensors were set to zero deformation at a vertical stress level of 0.5 MPa. The specimens were first subject to two normal loading cycles from 0.5 to 10.0 MPa. For each cycle, the normal stress was increased from 0.5 MPa up to 10.0 MPa and then decreased back to 0.5 MPa. Shearing was done at 3 different levels of normal stress. After the shearing displacement had taken place (at each normal stress level), it was suggested that the joints should be repositioned in their original positions before the new normal stress level was applied and the new shearing displacement began. After communication between NGI and SKB it was agreed upon not to reposition the joints after each normal stress level, but to continue the shearing displacement for about 3 mm at each stress level. The maximum shearing length in the NGI apparatus is 9 mm. However, in practice it proved to be difficult to determine residual shear strengths for each of the three shearing stages over only 9 mm. The final shearing lengths were therefore as follows:

~3 mm for loading cycle B,

~5.7 mm for loading cycle C,

~9 mm, reposition of specimen to original position, for loading cycle D.

The specimens were finally tested according to Table 4-1.

The LVDTs, both for vertical deformation and for shear displacement, were zeroed after the specimens had been loaded to 0.5 MPa vertical stress. A correction factor is added in the calculations for the effective joint area that is continuously changing while shearing. After the first shearing length is completed, the joint is placed again (pulled back) in its original position without blowing away the shear particles, “dust” that has been produced.

Table 4-1. Overview of the loading program for the DST tests.

Loading cycle	Normal stress during shearing	Comments	Plots
A		Normal loading of the joint from 0.5 to 10.0 MPa, 2 load cycles	Vertical stress vs. vertical displacement
B	σ_n = 0.5 MPa	Shearing until peak shear stress occurs and residual shear stress is clearly defined. Total shearing of about 3 mm Unloading of shear stress	Shear stress vs. shear displacement and vertical displacement vs. shear displacement
C	σ_n = 5.0 MPa	Shearing until peak shear stress occurs and residual shear stress is clearly defined. Total shearing of about 5.7 mm (continuation from the 3 mm above) Unloading of shear stress	Same as B
D	σ_n = 20.0 MPa	Joint placed in original position, thereafter it is sheared for about 9 mm. Final unloading	Same as B

4.1 Description of the samples

The tested specimens were of fine-grained granodiorite, see Table 4-2. They were cut and specially prepared in a hard epoxy mix in order to fit the direct shear apparatus at NGI. All specimens were tested in natural dry conditions (i.e. no attempt was made to wet or dry the specimens, except that the water coming in contact with the specimens during the cutting process was wiped away). No attempt was made to prevent evaporation from the specimens. In other words, the specimens were tested at natural dry conditions at room temperature (i.e. at about 19°C and roughly 25% relative humidity).

The tested specimens from KFM01A are listed in the table below. Specimen with ID FM01A-117-13 was damaged during preparation and it was not possible to test it.
A more detailed geological description of the joints is given in SKB mapping (Boremap).

Table 4-2. Overview over the tested specimens.

Borehole	Depth (m)	ID number	NGI test No.	Rock type	Joint set No *	Minerali sation	Joint Roughness
KFM01A	235.76	F01-117-2	DST211	Fine-grained granodiorite	Joint set 1	Hematite calcite	Planar
KFM01A	230.21	F01-117-4	DST212	Fine-grained granodiorite	Joint set 1	Hematite calcite	Planar, slightly rough
KFM01A	229.51	F01-117-6	DST213	Fine-grained granodiorite	Joint set 1	Hematite calcite	Planar
KFM01A	234.5	F01-117-8	DST214	Fine-grained granodiorite	Joint set 1	Chlorite calcite	Planar
KFM01A	390.33	F01-117-10	DST215	Fine-grained granodiorite	Joint set 1	Hematite calcite	Planar, slightly stepped

*The joint set number depends on the angle of intersection between the joint plane and the borehole axis and is given in Table 4-3 below.

Table 4-3. Correlation of the joint set number and the intersection angle between the joint plane and the borehole axis.

Joint set number	Angle of intersection in degrees
Set 1 (steep joints)	0-30°
Set 2 (ca 45 degrees joints)	30-60°
Set 3 (sub-horizontal joints)	60-90°

4.2 Testing

Several calibration tests were carried out by the end of February and until the beginning of March 2004. These tests were run in order to be able to correct the test results for false deformations. A steel specimen with the same shape and dimensions as a test specimen with a joint at an angle of about 30 degrees w.r.t the borehole axis (which is approximately the average angle of the tested specimens) was used for calibration purposes (see Figure 4-1). The epoxy mix used to fix the steel specimen to the metal ring was a mixture of dolomite powder and epoxy. The compressive strength of the epoxy mix before adding any extra dolomite powder is according to the manufacturer, 90 MPa. After consulting the manufacturer and in order to be able to increase the strength, more dolomite powder was added to the epoxy mix in order to increase the compressive strength. However, if too much dolomite is added, the epoxy mixture will be too stiff for the casting process to be successful. Different epoxy mixtures were tried. The same loading path as the one followed during the tests on rock was applied to the specimen. The results of the final test on the steel specimen are shown in Figures 4-2 and 4-3 below.

The corrections for false deformations used to calculate vertical and horizontal deformations are based on simplified versions of the observed curves shown in Figures 4-2 and 4-3.

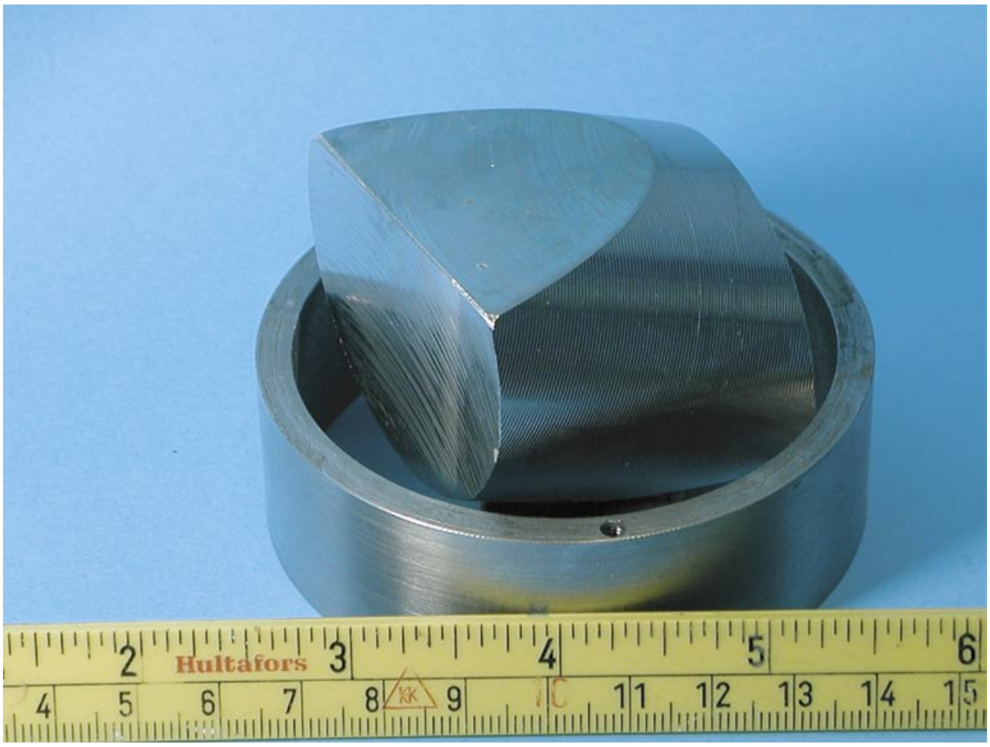

Figure 4-1. Photogragh of the specially shaped steel specimen just before epoxy is poured around it.

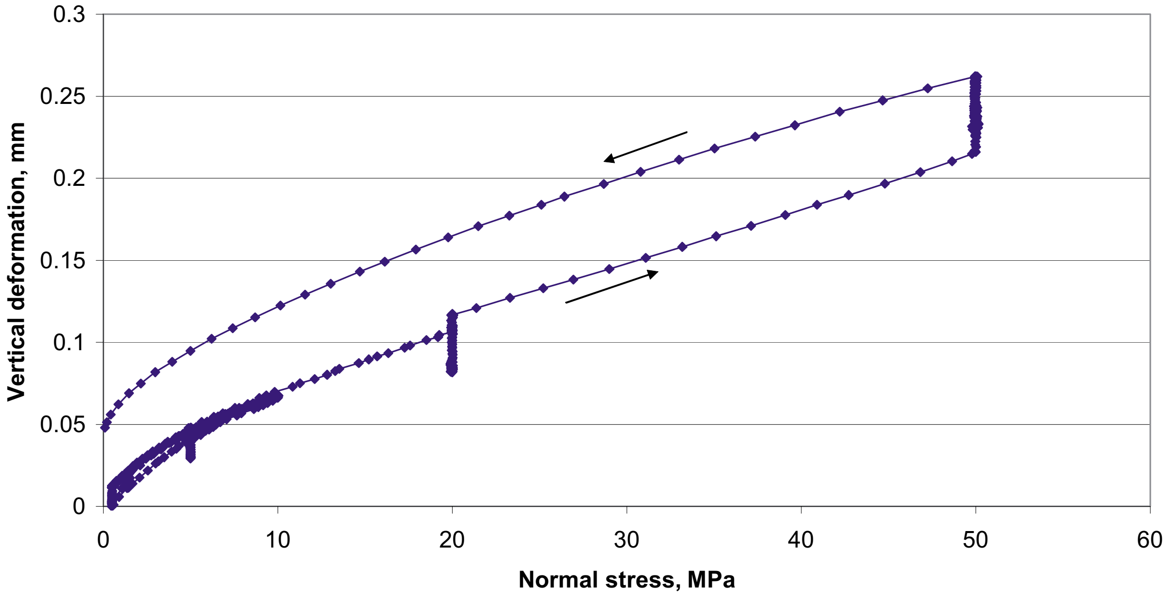

Figure 4-2. Vertical false deformations of the DST apparatus when loading the steel specimen with improved epoxy mix.

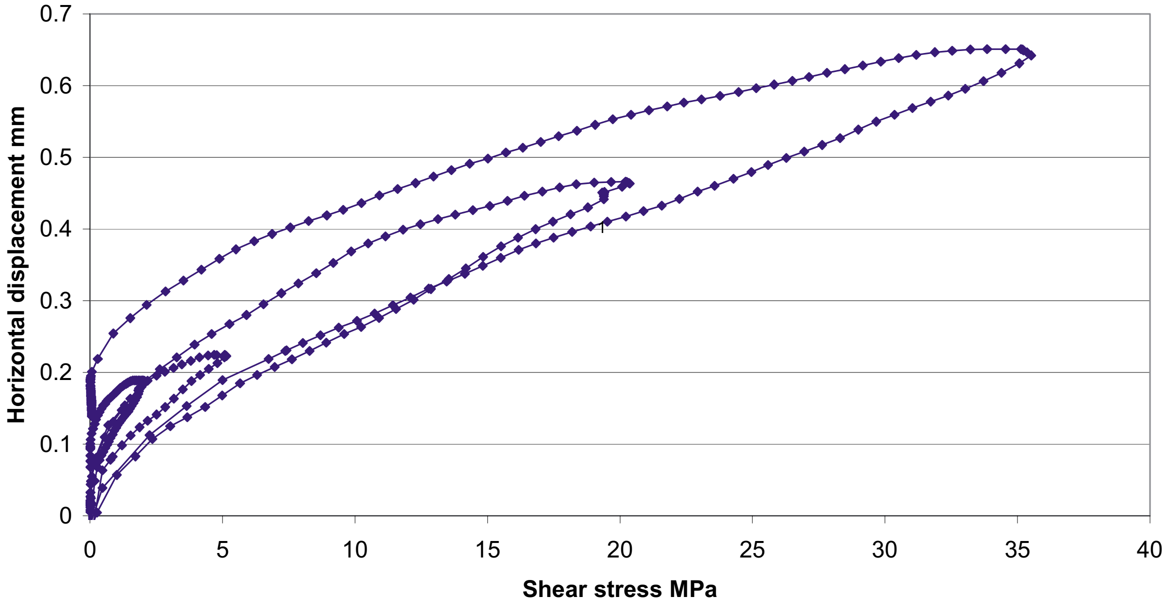

Figure 4-3. Horizontal false deformations of the DST apparatus when loading the steel specimen with improved epoxy mix.

The maximum stresses applied to the specimens during this testing programme resulted in false deformations of the order of 0.11 mm for a normal stress of 20.0 MPa and of about 0.46 mm for a shear stress of 20 MPa. The system was also tried for a normal stress up to 50 MPa, and a shear stress of 35 MPa.

4.3 Nonconformities

None.

5 Results

For the KFM01A borehole at Forsmark, five DST tests were performed. The detailed results for each test plus photographs of the respective specimen before and after the tests are presented in Figures A.1 to A.25 in Appendix A.

The figures in the appendix show:

- vertical (normal) stress versus vertical displacement for loading cycle A (see Table 4-1 for loading program for the DST tests),
- shear stress versus shear displacement for loading cycles B, C and D,
- vertical displacement versus shear displacement for loading cycles B, C and D,
- photographs of the specimen before and after testing.

5.1 Description and presentation of the specimens

Summaries of the obtained results are listed in Table 5-1. All DST tests were performed on cores from joint set 1. Specimen number DST 216 with ID number F01-117-13 from depth 699.91 m was unfortunately damaged during preparation and was not possible to test. The results in Table 5-1 can also be found in the database SICADA under field note no 96.

The following points may be noted in connection with Table 5-1:

- The peak shear stress for a given normal stress level is the highest value recorded at this level. The residual shear stress for a given normal stress level is the average shear stress of the last part of shearing at this level.

Table 5-1. Result list for all direct shear tests for borehole KFM01A.

Borehole number	Specimen depth	ID number	NGI's test number	Specimen area, cm^2	Normal stress at 0.5 MPa		Normal stress at 5.0 MPa		Normal stress at 20.0 MPa	
					Peak shear stress at 0.5 Mpa	Residual shear stress MPa	Peak shear stress at 5.0 MPa	Residual shear stress MPa	Peak shear stress at 20.0 MPa	Residual shear stress MPa
KFM01A	235.76	F01-117-2	DST211	24.7	1.40	0.80	4.38	3.09	16.22	13.90
KFM01A	230.21	F01-117-4	DST212	24.2	1.72	0.89	4.68	3.50	18.04	11.60
KFM01A	229.51	F01-117-6	DST213	24.3	2.11	0.84	4.92	4.76	15.12	14.70
KFM01A	234.5	F01-117-8	DST214	24.4	1.57	0.88	4.87	3.36	16.28	13.65
KFM01A	390.33	F01-117-10	DST215	23.2	1.51	1.10	5.43	4.59	16.29	12.00
		maximum value MPa		24.70	2.11	1.10	5.43	4.76	18.04	14.70
		average value MPa		24.16	1.66	0.90	4.86	3.86	16.39	13.17
		minimum value MPa		23.20	1.40	0.80	4.38	3.09	15.12	11.60

5.2 Results of the entire test series

Table 5-2 shows the corresponding tilt test results (arithmetic mean values of joint properties) for the various joint sets in borehole KFM01A /Chryssanthakis, 2003/.

Table 5-2. Arithmetic mean of JCS_o, JRC_o, Φ_r and Φ_b -values, Borehole KFM01A /Chryssanthakis, 2003/.

Fracture set	JRC_o (tilt)	JCS_o MPa	Φb (°)	Φr (°)	Number (tilt)	Number (profiles)
Set 1	6.6	90.41	28.7	24.2	15	15
Set 2	6.3	95.3	28.5	24.0	12	12
Set 3	5.6	87.8	29.4	24.4	14	14
Mean/Total	6.1	90.9	28.9	24.2	41	41

5.3 Discussion

The DST tests performed at NGI can be described as routine rock mechanical tests for determining the shear characteristics of rock joints. The technical staff, mentioned in Section 1, performed all DST tests, calibrations of the LVDTs and transducers and dummy tests (i.e. tests for determination of false deformations). Emphasis was given to the design of the epoxy mix used to fix the specimens in the DST apparatus in order to achieve a mixture stiff enough for the applied stresses. The logging frequency has been 10 s during loading step A and the shearing velocity approximately 6 mm/hour for loading step B and 12 mm/hour for loading step D. The logging frequency for the three shearing stages has been 20 s.

For test number DST 211 and DST 212, and to a lesser extent for test DST 214, stick and slip behaviour is observed after the peak shear stress has occurred during loading cycle D. The residual shear stress value is then estimated as the mean value for approximately the last 2 mm of shearing.

For some of the tests listed in the appendix, for example DST 211, the shear displacement values have a negative sign in the beginning of loading step D. This is because the specimen could not be repositioned at exactly zero deformation position (although it was tried). These initial negative values do not have any effect on the test results.

The spreading of the results is larger during the first loading step B (normal stress 0.5 MPa) than during loading step C (normal stress 5 MPa) and D (normal stress 20 MPa). This may be expected since the shearing of the joint asperities takes place mainly during loading step B. The specimens have different joint roughness coefficients despite the fact that most of them are characterized as planar joints. The joint asperities are considered to be less important during loading steps C and D.

The residual shear stress values are considered to be rather high compared to the peak shear stress values. This is not surprising since the specimens have a relative high JCSo value and a high uniaxial compressive strength.

It was decided not to add any trend lines for the residual shear stress values since each test behaved in a different way. As a rule of thumb, the residual value quoted in this report is the mean shear stress value for approximately the last 1 mm of shearing during loading step B. For loading steps C and D the residual shear stress value is the mean shear stress value for approximately the last 2 mm of shearing.

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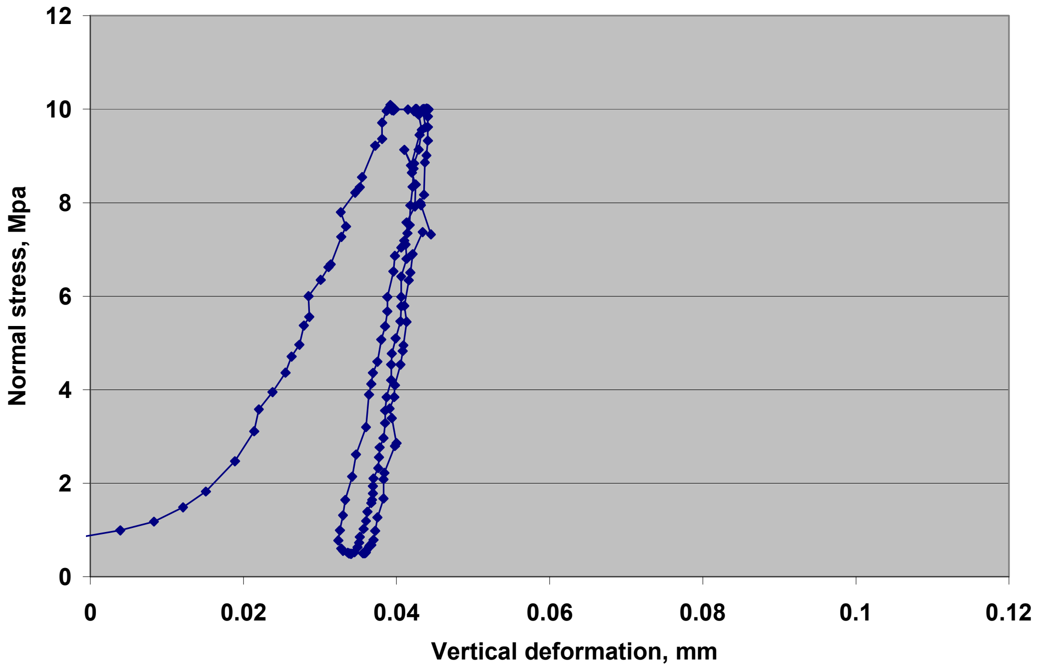
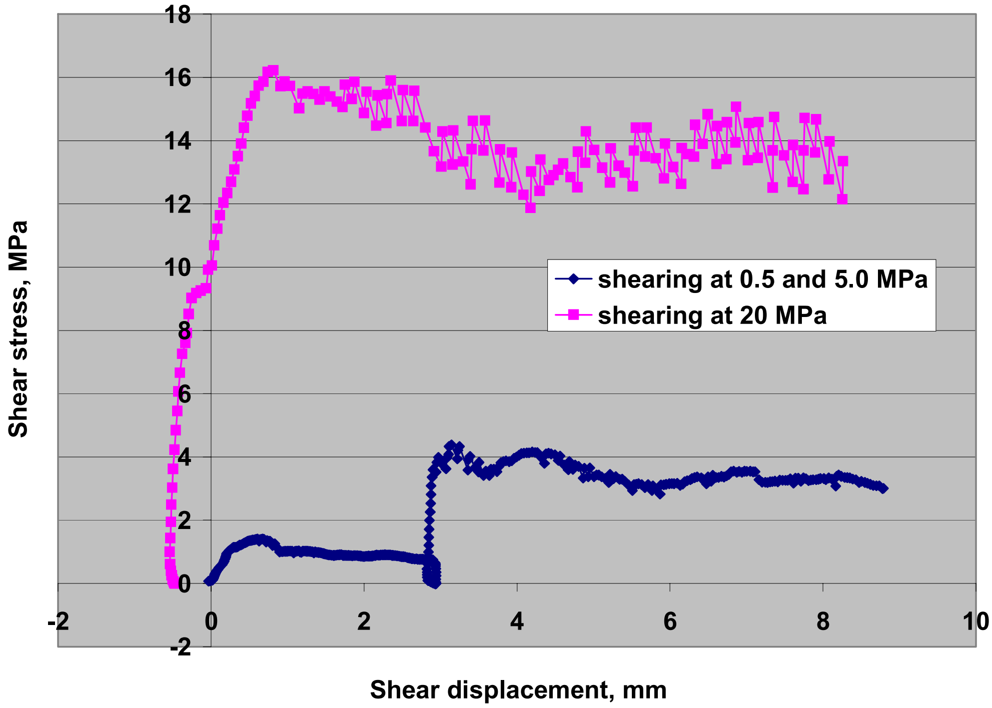
Chryssanthakis P, 2003. Borehole KFM01A. Results of tilt testing. SKB P-03-108, June 2003.

ISRM standards, 1981. Suggested methods for Direct Shear Stress testing. Editor E.T Brown, Published for the Commission on Testing Methods, Pergamon Press.

Appendix A

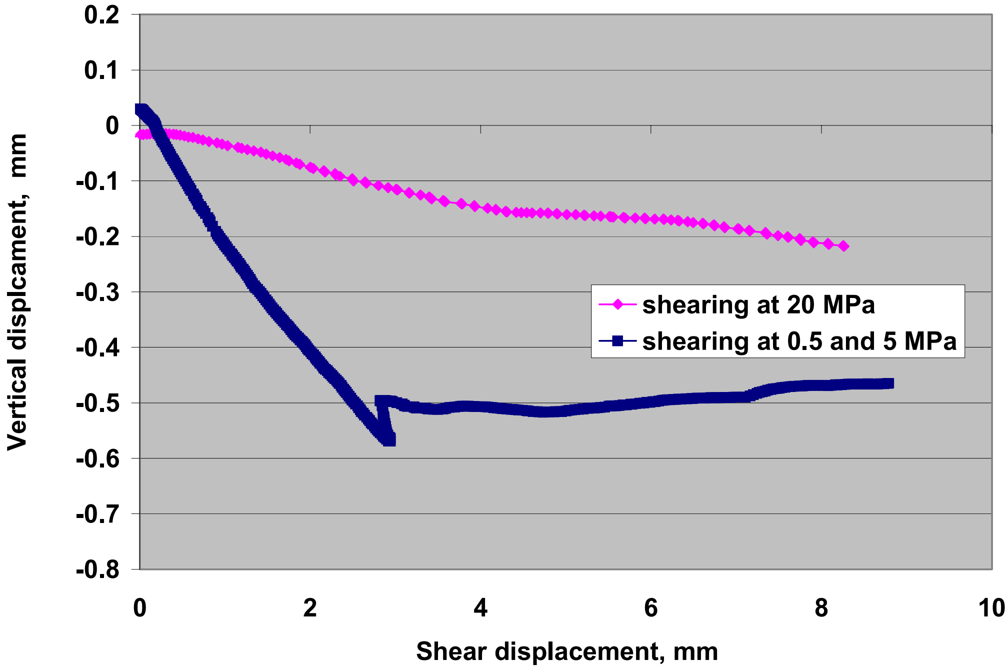
The main results from direct shear testing





Test DST 211

Borehole KFM01A, ID F01-117-2, depth 235.76 m
Figure A.1 (top): vertical stress versus vertical displacement for loading cycle A
Figure A.2 (bottom): shear stress versus shear displacement for loading cycle B, C, and D

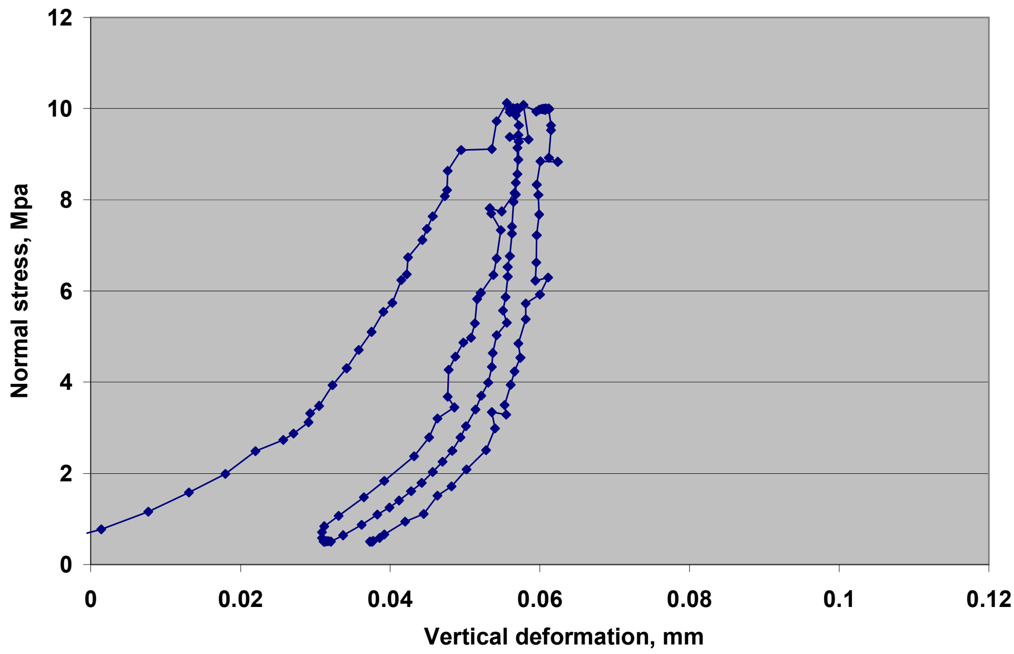


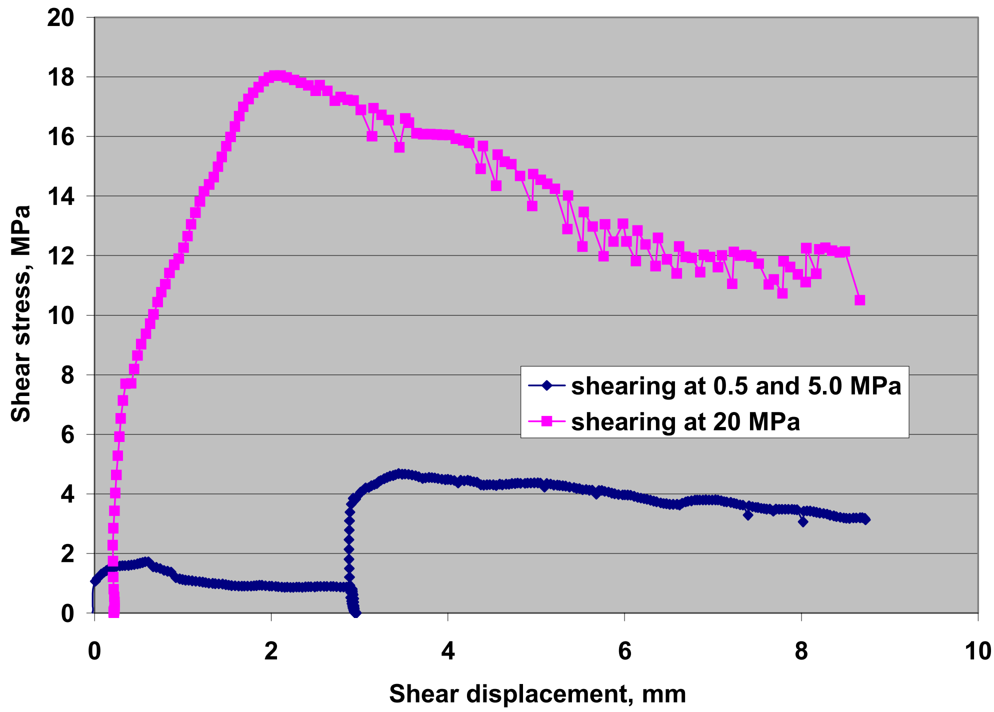
Test DST 211

Borehole KFM01A, ID F01-117-2, depth 235.76 m
Figure A.3: Normal displacement versus shear displacement for loading cycle B, C, and D (dilation)

Test DST 211

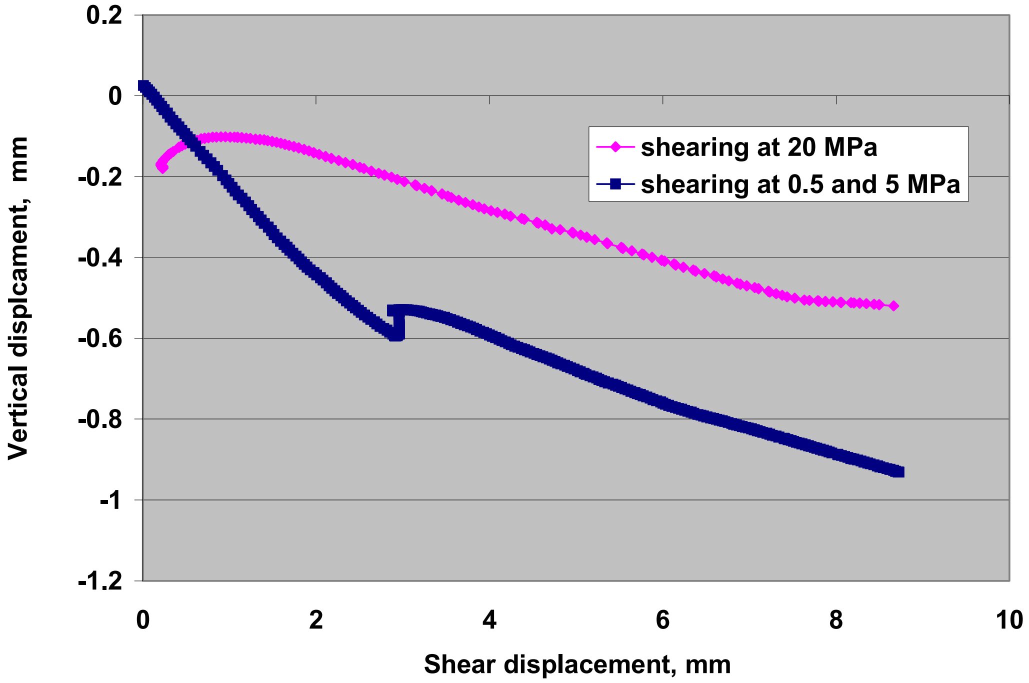
Borehole KFM01A, ID F01-117-2, depth 235.76 m
Figure A.4 (top): before testing
Figure A.5 (bottom): after testing





Test DST 212

Borehole KFM01A, ID F01-117-4, depth 230.21 m
Figure A.6 (top): vertical stress versus vertical displacement for loading cycle A
Figure A.7 (bottom): shear stress versus shear displacement for loading cycle B, C, and D

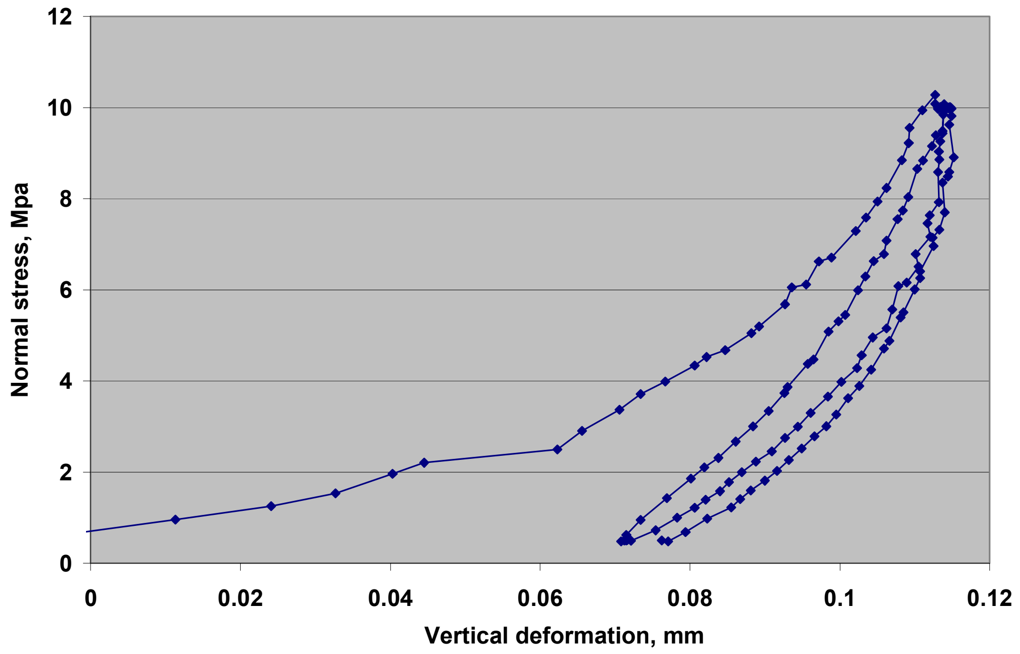


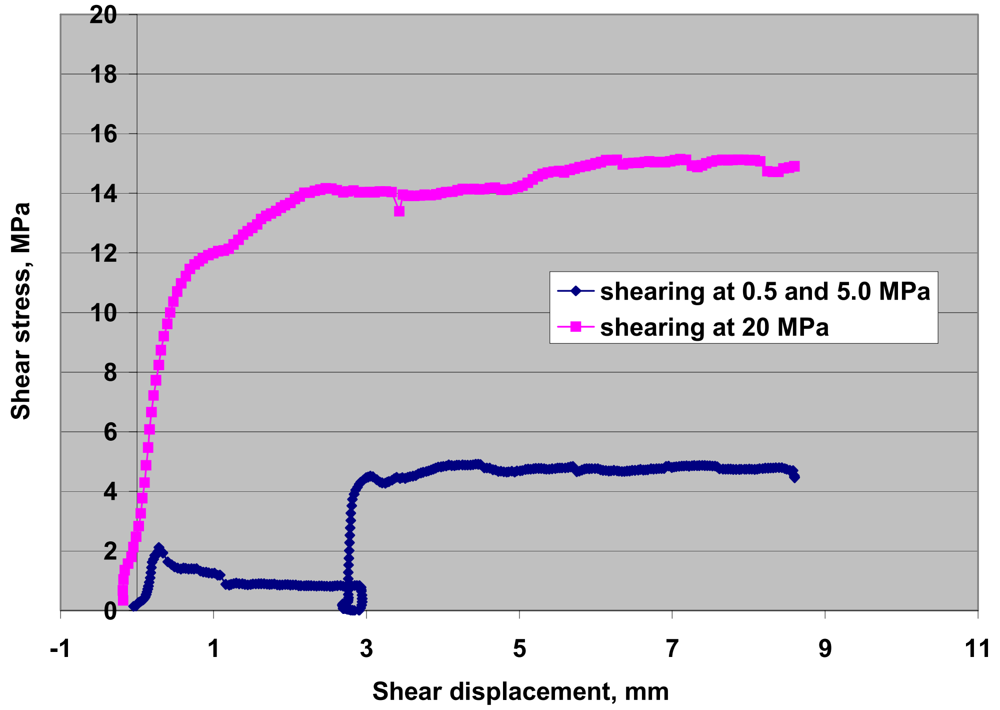
Test DST 212

Borehole KFM01A, ID F01-117-4, depth 230.21 m
Figure A.8: Normal displacement versus shear displacement for loading cycle B, C, and D (dilation)

Test DST 212

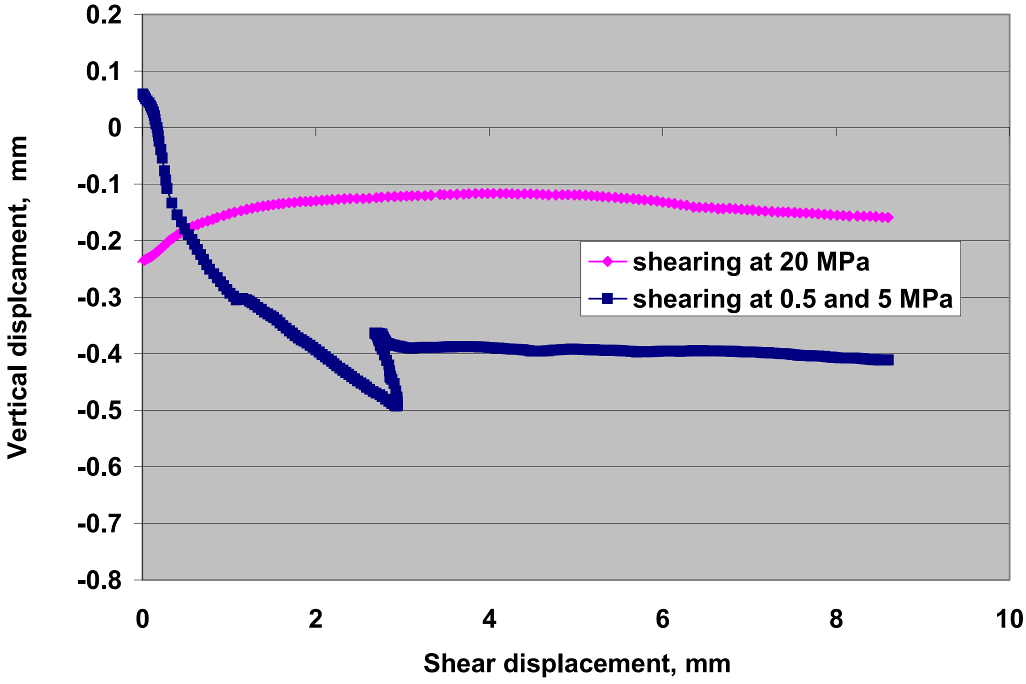
Borehole KFM01A, ID F01-117-4, depth 230.21 m
Figure A.9 (top): before testing
Figure A.10 (bottom): after testing





Test DST 213

Borehole KFM01A, ID F01-117-6, depth 229.51m
Figure A.11 (top): vertical stress versus vertical displacement for loading cycle A
Figure A.12 (bottom): shear stress versus shear displacement for loading cycle B, C, and D

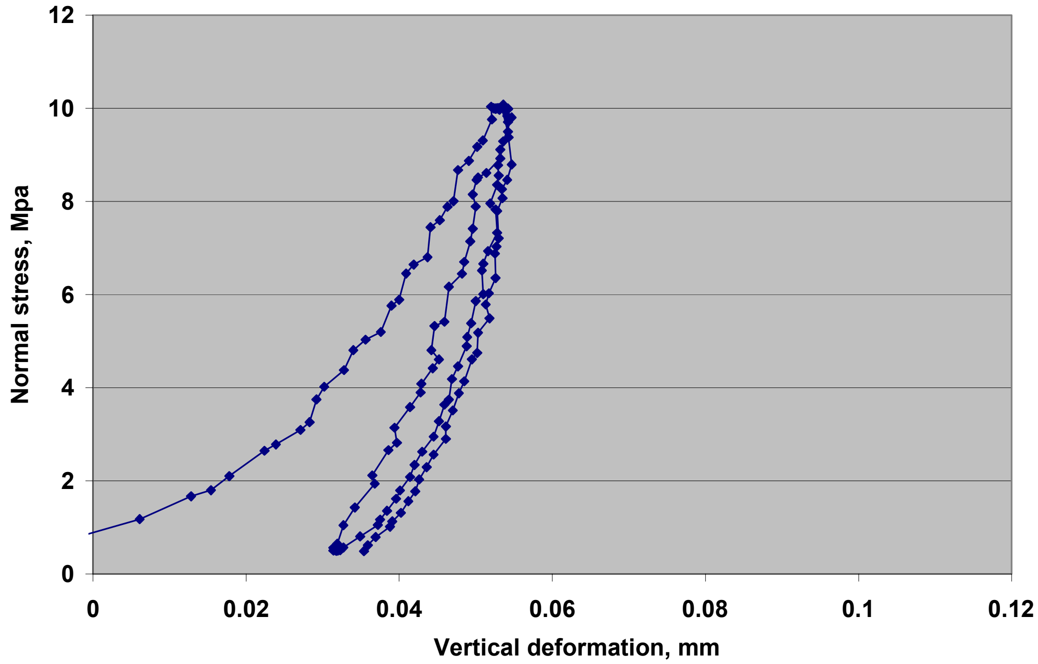


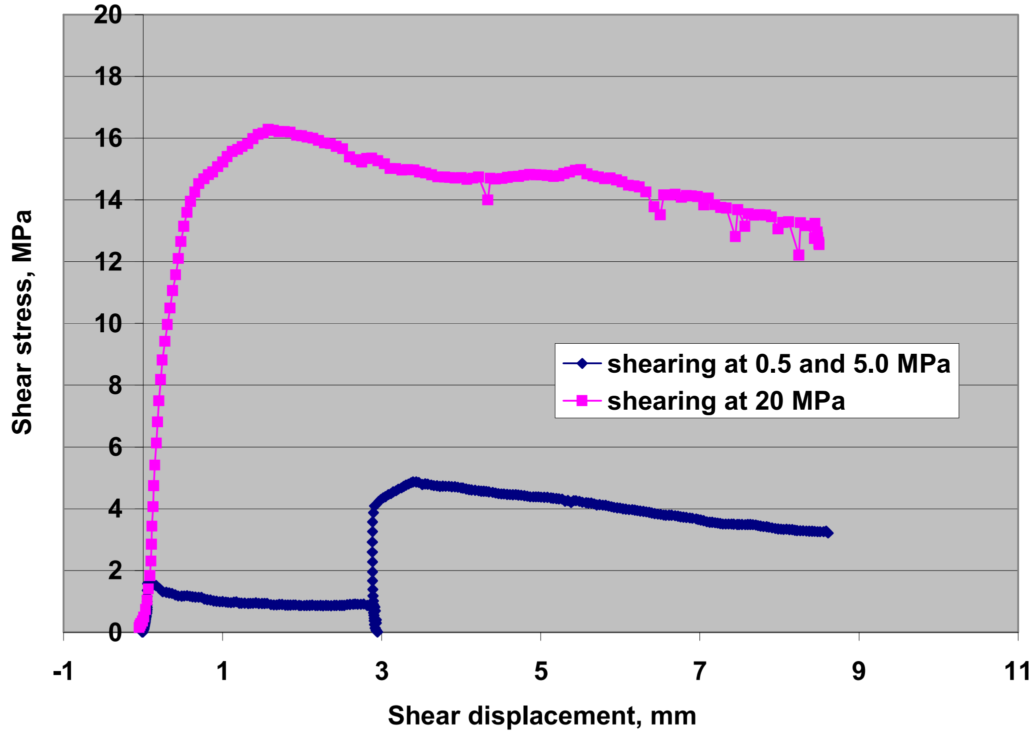
Test DST 213

Borehole KFM01A, ID F01-117-6, depth 229.51m
Figure A.13: Normal displacement versus shear displacement for loading cycle B, C, and D (dilation)

Test DST 213

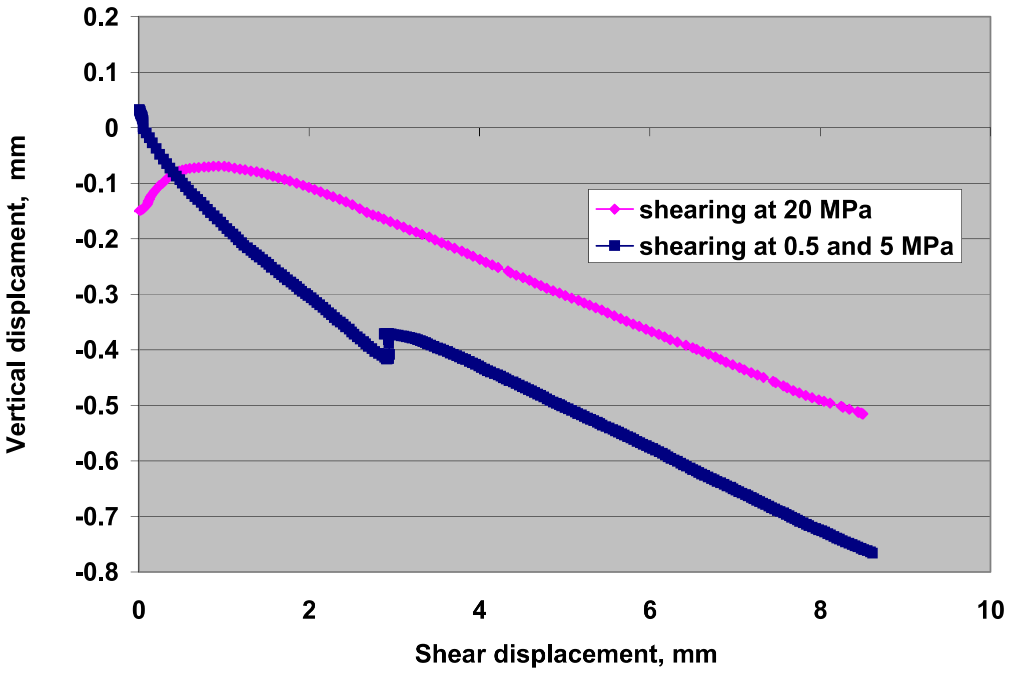
Borehole KFM01A, ID F01-117-6, depth 229.51m
Figure A.14 (top): before testing
Figure A.15 (bottom): after testing





Test DST 214

Borehole KFM01A, ID F01-117-8, depth 234.50 m
Figure A.16 (top): vertical stress versus vertical displacement for loading cycle A
Figure A.17 (bottom): shear stress versus shear displacement for loading cycle B, C, and D

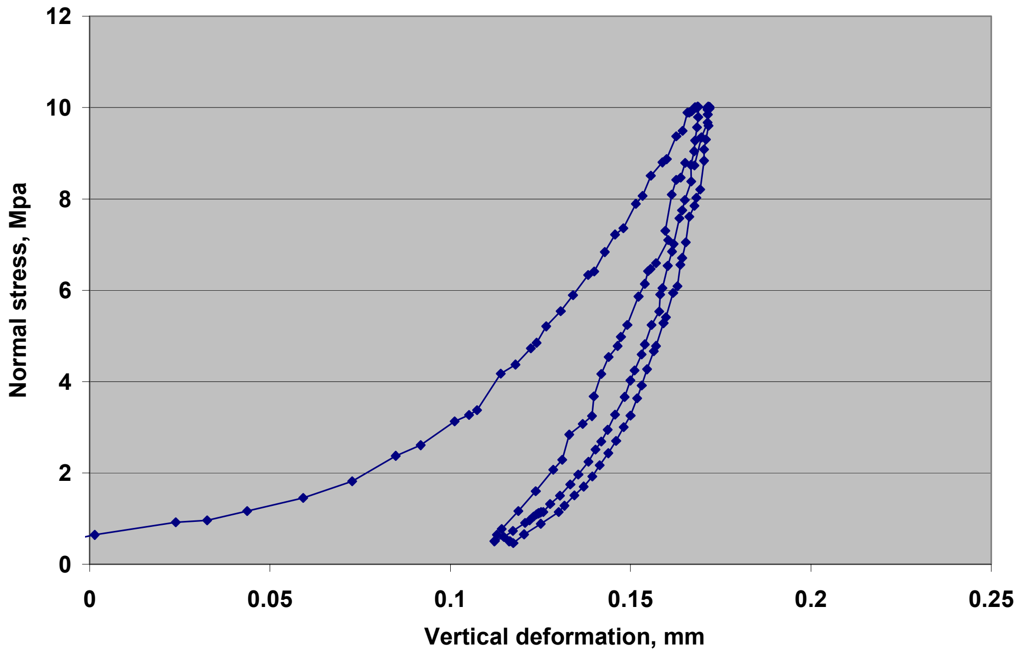


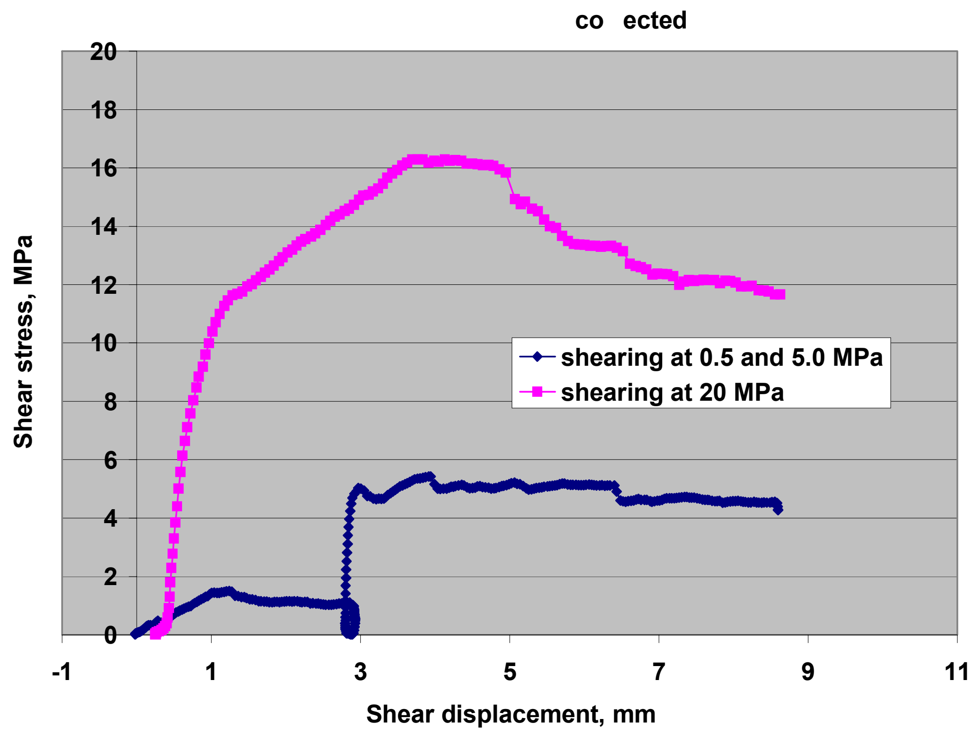
Test DST 214

Borehole KFM01A, ID F01-117-8, depth 234.50 m
Figure A.18: Normal displacement versus shear displacement for loading cycle B, C, and D (dilation)

Test DST 214

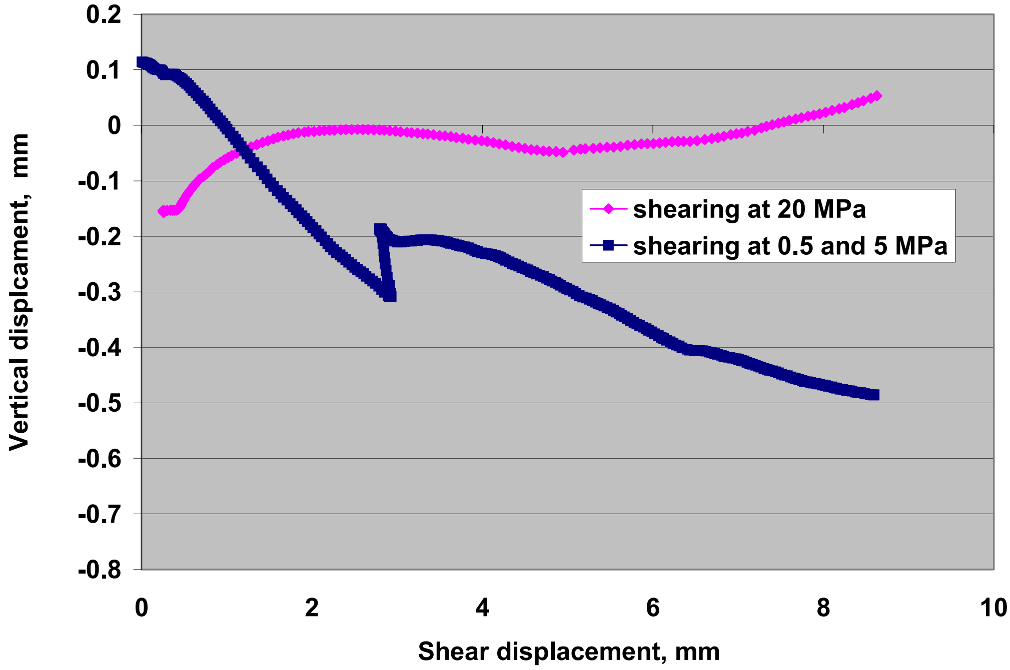
Borehole KFM01A, ID F01-117-8, depth 234.50 m
Figure A.19 (top): before testing
Figure A.20 (bottom): after testing





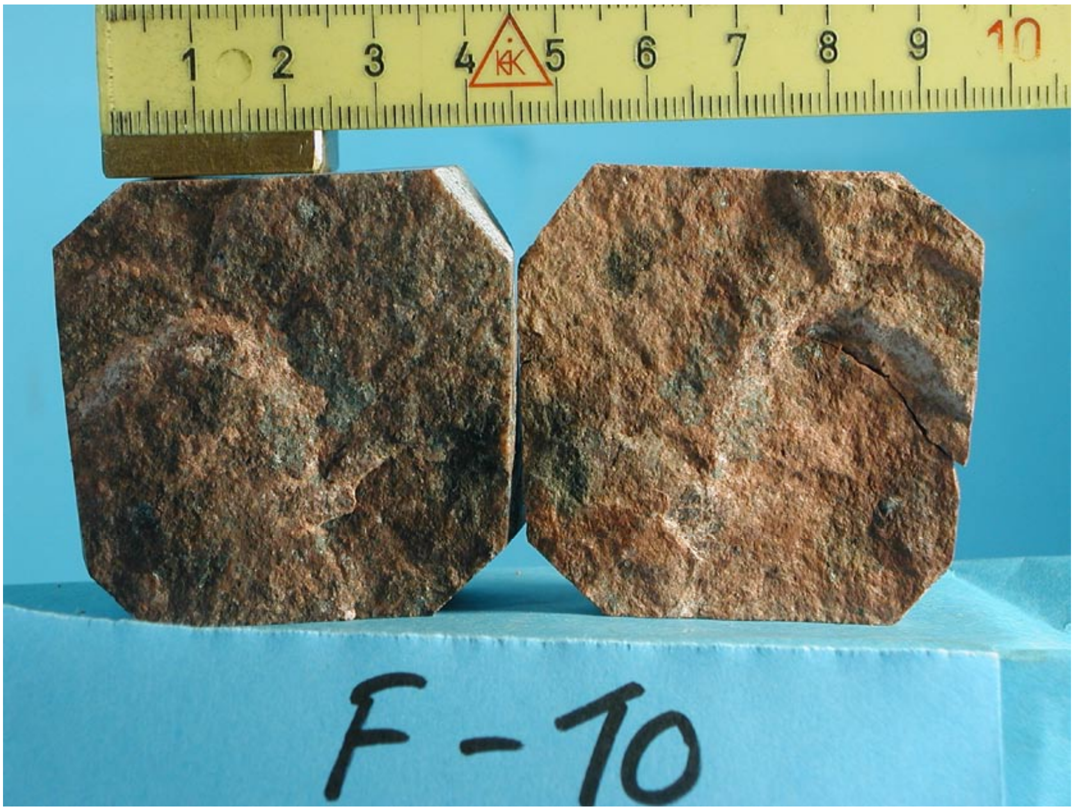
Test DST 215

Borehole KFM01A, ID F01-117-10, depth 390.33 m
Figure A.21 (top): vertical stress versus vertical displacement for loading cycle A
Figure A.22 (bottom): shear stress versus shear displacement for loading cycle B, C, and D



Test DST 215

Borehole KFM01A, ID F01-117-10, depth 390.33 m
Figure A.23: Normal displacement versus shear displacement for loading cycle B, C, and D (dilation)



Test DST 215

Borehole KFM01A, ID F01-117-10, depth 390.33 m
Figure A.24 (top): before testing
Figure A.25 (bottom): after testing