R-05-21

Rock mechanics characterisation of the rock mass – summary of primary data

Preliminary site description Simpevarp subarea – version 1.2

Flavio Lanaro, Berg Bygg Konsult AB

Anders Fredriksson, Golder Associates

December 2005

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1402-3091
SKB Rapport R-05-21

Rock mechanics characterisation of the rock mass – summary of primary data

Preliminary site description Simpevarp subarea – version 1.2

Flavio Lanaro, Berg Bygg Konsult AB

Anders Fredriksson, Golder Associates

December 2005

Abstract

The present report summarises the laboratory results performed on samples of intact rock and natural fractures collected at Simpevarp in relation to the Preliminary Site Descriptive Modelling, version 1.2.

Intact rock samples from borehole KSH01A and KSH02A were selected to represent two rock types at the Site: fine-grained dioritoid (code 501030) and quartz monzonite to monzodiorite (code 501036). Uniaxial, triaxial and tensile tests were also conducted. Based on the tests results, several of the strength parameters of the intact rock were determined: i) the uniaxial compressive strength; ii) the Hoek & Brown's strength parameters; iii) the Coulomb's strength parameters and; iv) the tensile strength. The dioritoid has an average uniaxial compressive strength of about 205 MPa while the monzonite has a uniaxial strength of about 161 MPa. The Coulomb's approximation of the experimental failure envelope returns the apparent cohesion and friction angle of the intact rock for minimum principal stress between 0 and 15 MPa. The cohesion and friction angle of the quartz monzonite are about 20 MPa and 60°, respectively. For the dioritoid, these parameters are about 33 MPa and 53°, respectively. Indirect tensile tests show that the two rock types exhibit almost the same indirect tensile strength (around 18–19 MPa). Some results were also obtained at the Helsinki University of Technology (HUT) for comparison.

The mechanical tests show that the Young's modulus of the intact rock from uniaxial compression tests is 85 GPa for the fine-grained dioritoid and 78 GPa for the monzonite, respectively. In uniaxial conditions, the Poisson's ratio of the dioritoid is 0.26 and that of the monzonite is 0.27, respectively. From the triaxial tests, a Young's modulus of about 78 GPa was observed for both rock types. In triaxial conditions, the Poisson's ratio of the two rock types is also very close and reduces to about 0.22.

Tilt tests, normal load and direct shear test results were available for natural rock fractures samples from boreholes KSH01A, KSH02A, KLX02 and KAV01. The tilt tests return, on average, a basic friction angle of 31° (standard deviation 1.8°), a JRC_0 of around 6, a JCS_0 of around 63 MPa and a residual friction angle of 26° (wet). The Coulomb's peak friction angle and peak cohesion from tilt tests for a normal stress range between 0.5 and 20 MPa were calculated to 34° and 0.37 MPa, respectively. The dilation angle of the natural fractures in peak strength conditions can be obtained by subtracting the basic friction angle from the peak friction angle.

Direct shear testing was performed by two laboratories (NGI and SP) on different sets of fracture samples. The NGI Laboratory tested seven samples and obtained an average peak friction angle of 34° and peak cohesion of 1.2 MPa, respectively.

The SP Laboratory tested 28 samples. The peak friction angle from SP's tests was on average 32° and the peak cohesion 0.5 MPa, respectively. Besides the strength, also the normal stiffness and shear stiffness of the fractures were determined. On average, the normal stiffness was 100 MPa/mm while the shear stiffness 30 MPa/mm. More credit was given to the SP Laboratory results due to the larger amount of tested samples. For these results, a weak negative correlation was observed between cohesion and friction angle.

Sammanfattning

Denna rapport sammanfattar de laboratorieresultat på intakt berg och naturliga sprickor som samlats in i Simpevarp i samband med den Platsbeskrivande modellen i version 1.2.

Intakta bergprov togs i finkornig dioritoid (kod 501030) och kvartsmonzonit till monzodiorit (kod 501036) från borrhål KSH01A och KSH02A. Enaxiella tryck-, triaxiella tryck och indirekt drag-hållfasthetstester genomfördes. Baserat på dessa resultat har man kunnat bestämma: i) den enaxiella tryckhållfastheten; ii) Hoek & Browns parametrar; iii) Coulombs parametrar; iv) draghållfastheten. Dioritoiden har en medel-enaxiell tryckhållfasthet på ca 205 MPa medan för monzoniten är den 161 MPa. Det experimentella brottkriteriet kunde approximeras med Coulombs kriterium så att den skenbara kohesionen och friktionsvinkel för det intakta berget kunde beräknas för en minsta huvudspänning mellan 0 och 15 MPa. För monzoniten är kohesionen ca 20 MPa och friktionsvinkeln 60°. För dioritoiden är kohesionen ca 33 MPa och friktionsvinkeln 53°. Den indirekta draghållfastheten är nästan den samma för båda bergarterna och deras medelvärden ligger mellan 18 och 19 MPa. På Helsingfors Tekniska Universitet (HUT) genomfördes några jämförelsetester.

Laboratorietesterna visar att Youngmodulen under enaxiell belastning är 85 GPa för dioritoiden respektive 78 GPa för monzoniten. Poissonstalet från samma tester är 0.26 för dioritoiden respektive 0.27 för monzoniten. Elasticitetsmodulen kan också bestämmas från triaxiella tester och för båda bergarterna observerades ett värde på 78 GPa. De triaxiella testerna visar att Poissonstalet minskar till 0.22 för båda bergarterna.

Tilttester, normalbelastningstester och skjuvhållfasthetstester genomfördes på sprickor från borrhål KSH01A, KSH02A, KLX02 och KAV01. Baserat på tilttesterna kan man räkna basfriktionsvinkeln (31° med standardavvikelse 1.8°), råhetsparametern JRC_0 (ca 6), sprickytshållfastheten JCS_0 (ca 63 MPa) och resterande friktionsvinkeln (blöt, ca 26°). Från Barton-Bandiskriteriet kan man räkna fram max-koesionen och max-friktionsvinkeln (”peak”): för normalspänningar mellan 0,5 och 20 MPa är dessa parametrar i genomsnitt 0,37 MPa respektive 34°. Dilatationsvinkeln beräknas som skillnaden mellan max-friktionsvinkeln och basfriktionsvinkeln..

Skjuvtester genomfördes av två laboratorier (NGI och SP) på olika set av sprickor. Sju prover testades av NGI och resultatet var en max-kohesion på 1,2 MPa och en max-friktionsvinkel på 34°.

SP laboratorium testade sammanlagt 28 sprickprover. Max-friktionsvinkeln från dessa tester var ca 32° medan max-kohesionen låg på ca 0,5 MPa. Utöver hållfastheten kunde man också bestämma normal- och skjuvstyvheten hos sprickorna. I genomsnitt var normalstyvheten runt 100 MPa/mm medan skjuvstyvheten var runt 30 MPa/mm. Mera tilltro tilldelades till SP-datan huvudsakligen tack vare det större antalet testade sprickprover. En svag negativ korrelation mellan kohesionen och friktionsvinkeln kunde också observeras i resultaten.

Contents

1 Introduction

The present report summarises the data that are the base for the Rock Mechanics Descriptive Model for Simpevarp version 1.2. The available primary data consists on laboratory results on intact rock and rock fractures. The data is considered as it was available in SICADA-database on June 17th, 2004. Direct shear test results are also included, which were delivered after this date.

Data were obtained from the following boreholes:

KSH01A: Intact rock (uniaxial, triaxial and indirect tensile tests), rock fractures (tilt and shear tests).

KSH02A: Intact rock (uniaxial, triaxial and indirect tensile tests), rock fractures (tilt and shear tests).

KAV01: Rock fractures (tilt and shear tests).

KLX02: Rock fractures (tilt tests).

Old laboratory tests from the Äspö Hard Rock Laboratory and Clab Facility were also compared with the new laboratory data for correspondent rock types /SKB 2004/.

The results are presented in this document for different end-users:

a) Empirical Approach.

b) Theoretical Approach.

c) Site Descriptive Modelling.

Here, the users can obtain specific information on Coulomb's and Hoek & Brown's Criterion parameters for the intact rock and Coulomb's parameters for the rock fractures. Barton-Bandis's Criterion parameters could not be determined for the direct shear tests due to the too marked linearity of the experimental results.

The Appendices show details on the frequency distributions of the parameters of the intact rock (Appendix 1) and the results from the tilt and direct shear tests (Appendix 2).

2 Intact rock

In this chapter, the results of the uniaxial compressive strength tests on intact rock samples are summarised both independently and together with the results of the triaxial compressive strength tests. The rock types represented are: fine-grained dioritoid (SICADA code 501030) and quartz monzonite to monzodiorite (code 501036).

2.1 Uniaxial compressive strength

The laboratory results of uniaxial compressive strength (UCS) on samples from borehole KSH01A and KSH02A at the SP Laboratory (the Swedish National Testing and Research Institute) /Jacobsson 2004ab/ are sorted according to rock type and the mean value and the standard deviation are determined (Table 2-1). The statistical description is completed by means of the minimum, maximum and most frequently occurring values.

In some cases, the records for each sample also refer to the presence of sealed fractures that could have affected the test behaviour. For this reason, these samples of fine-grained dioritoid are kept separated from the rest. The strength calculate based on all the tests is also given, independently of the rock type, and could be used to represent the mixture of the two main rock types, so common at Simpevarp.

In Figure 2-1 and Figure 2-2, the frequency distributions of the samples from Äspö HRL, Clab /SKB 2004/ and the results in the present report can be compared. It can be noticed that the Äspö and Clab data might contain a mixture of the rock types in Figure 2-2. This is particularly evident in the bimodal distribution of the Äspö results.

The results obtained at the HUT Laboratory (Helsinki University of Technology) /Eloranta 2004a/ on five samples of quartz monzonite gave an average uniaxial compressive strength of 170 MPa, thus confirming the results in Table 2-1.

Table 2-1. Summary of the results of uniaxial compressive tests performed on intact rock samples from borehole KSH01A and KSH02.

Rock type	Number of samples	Minimum UCS [MPa]	Mean UCS [MPa]	Frequent UCS [MPa]	Maximum UCS [MPa]	UCS Standard deviation [MPa]
Fine-grained dioritoid (metavolcanite, volcanite).	10	109	205	230	264	51
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	10	118	161	164	193	24
All intact rock samples	20	109	183	175	264	45
Fine-grained dioritoid with sealed fractures.	5	92	126	131	158	31
All samples and sealed fractures.	25	92	172	168	264	48

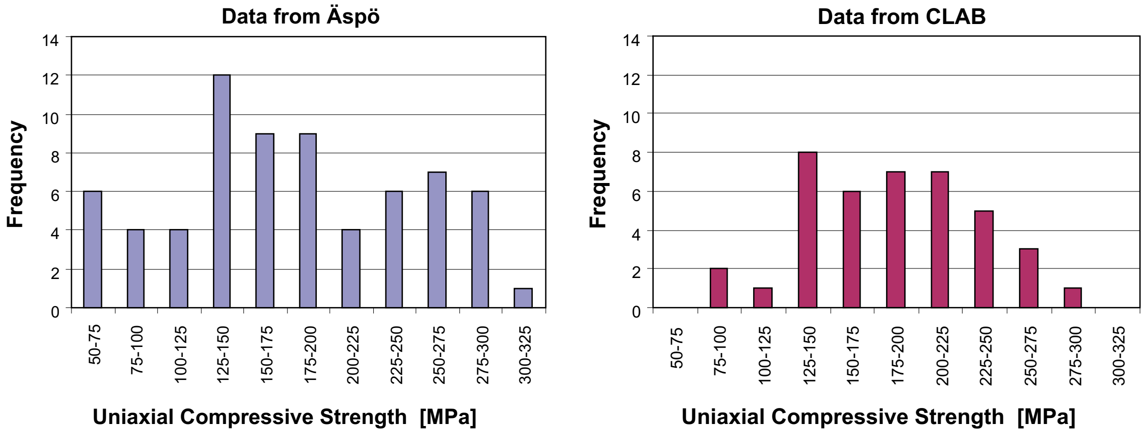


Figure 2-1. *Frequency distributions of the uniaxial compressive strength of all samples available from Äspö and Clab /SKB 2004/. The rock types were not specified in the sources.*

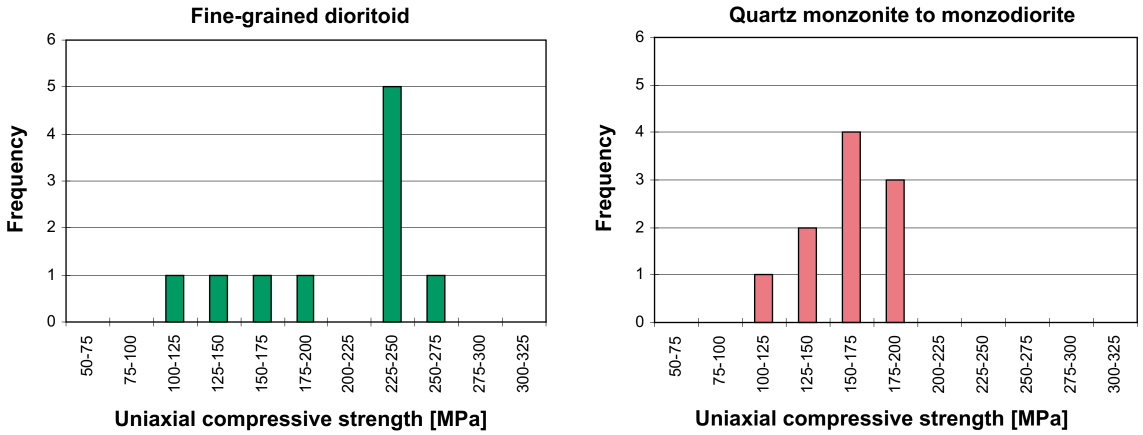


Figure 2-2. *Frequency distributions of the uniaxial compressive strength of the samples of fine-grained dioritoid and quartz monzonite to monzodiorite from borehole KSH01A and KSH02A.*

2.2 Triaxial compressive strength

Triaxial tests were also conducted on samples from boreholes KSH01A and KSH02A /Jacobsson 2004cd/. For each main rock type (fine-grained dioritoid and quartz monzonite to monzodiorite), these results were analysed together with the correspondent results from the uniaxial compressive tests. The records of the testing also indicate that some of the samples contained sealed fractures that dominated the failure behaviour. For this reason, these samples were grouped per se.

The laboratory results on intact rock samples were interpolated with the Hoek & Brown's Failure Criterion /Hoek et al. 2002/.

$$\sigma'_1 = \sigma'_3 + UCS_T \left(m_i \frac{\sigma'_3}{UCS_T} + 1 \right)^{0.5} \qquad (1)$$

where σ'_1 and σ'_3 are the maximum and minimum principal stresses and m_i is a strength parameter typical for each rock type. UCS_T is obtained by matching the uniaxial and triaxial test results and thus slightly differs from UCS in Section 2.1.

When analysing the laboratory results, the intact rock parameters in Table 2-2 are obtained. Although calculated in a slightly different way, these results of UCS are in rather good agreement with the values in Table 2-1 obtained from uniaxial tests only.

Based on the Hoek & Brown's Criterion, Coulomb's linear approximations were also calculated for a certain stress interval (between 0 and 15 MPa, Table 2-3). These linear approximations are shown in Figure 2-3 and Figure 2-4 for the fine-grained dioritoid and quartz monzonite to monzodiorite, respectively. The Hoek & Brown's Criterion also provides an estimation of the tensile strength of the intact rock that can be compared with the laboratory results in Section 2.3. The estimated tensile strength is also used to truncate the Columb's Criterion as shown in Figure 2-3 and Figure 2-4.

Five samples were also tested in triaxial compression conditions at the HUT Laboratory /Eloranta 2004b/. These results were not available at the time of compilation of this summary of the primary data and are therefore not included here.

Table 2-2. Parameters for the Hoek & Brown's Criterion based on the results of uniaxial and triaxial tests performed on intact rock samples from borehole KSH01A and KSH02.

Rock type	Number of samples	Minimum USCT [MPa]	mi	Mean UCST [MPa]	mi	Maximum UCST [MPa]	mi
Fine-grained dioritoid (metavolcanite, volcanite).	16	118.5	15.0	207.3	13.7	296.1	13.2
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	16	123.4	32.6	160.1	30.6	196.8	29.3
All intact rock samples.	32	106.0	23.8	183.3	21.1	260.4	20.0
Sealed fractures in intact rock.	11	55.0	19.8	122.2	16.5	189.4	15.5
All samples and sealed fractures.	43	77.4	21.0	168.2	19.3	262.1	18.2

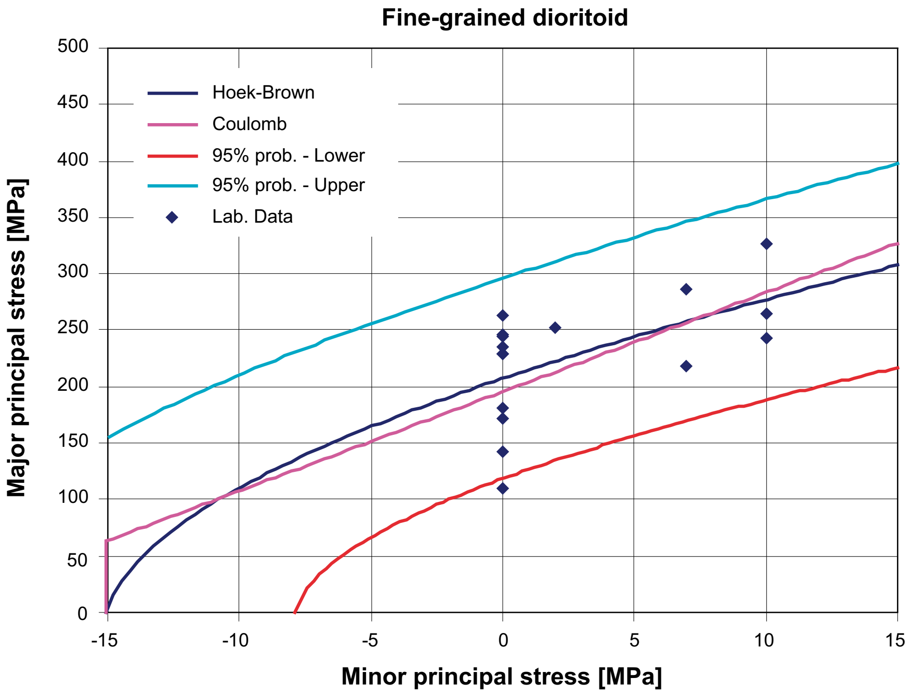


***Figure 2-3**. Hoek & Brown's and Coulomb's failure envelopes from uniaxial and triaxial tests for the fine-grained dioritoid.*

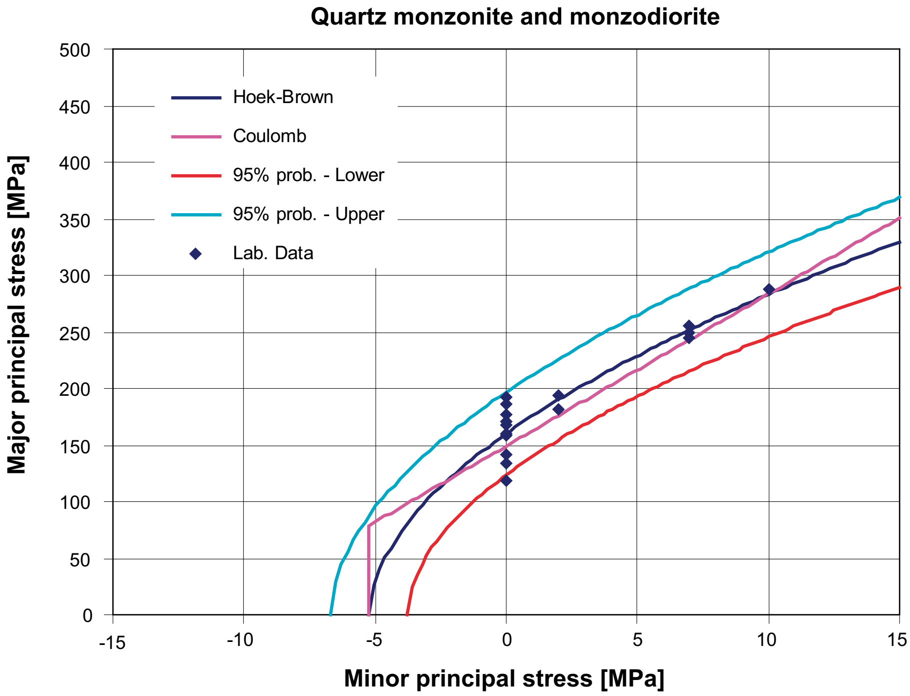


Figure 2-4. *Hoek & Brown's and Coulomb's failure envelopes from uniaxial and triaxial tests for the samples of quartz monzonite to monzodiorite.*

Table 2-3. Parameters for the Coulomb's Criterion based on the results of uniaxial and triaxial tests performed on intact rock samples from borehole KSH01A and KSH02.

Rock type	Number of samples	Minimum c' [MPa]	φ' [°]	Mean c' [MPa]	φ' [°]	Maximum c' [MPa]	φ' [°]
Fine-grained dioritoid (metavolcanite, volcanite).	16	19.3	51.2	33.0	52.7	47.1	53.5
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	16	16.5	58.7	20.3	59.5	24.3	60.1
All intact rock samples.	32	15.7	55.1	25.3	56.8	35.3	57.7
Sealed fractures in intact rock.	11	10.1	49.3	19.2	52.3	29.0	53.7
All samples and sealed fractures.	43	12.7	52.1	24.2	55.5	36.9	56.7

The values of the cohesion and friction angle are obtained for a confinement stress between 0 and 15 MPa.

2.3 Tensile strength

Indirect tensile tests were performed on samples from borehole KSH01A and KSH02A /Jacobsson 2004ef/. Another set of indirect tensile tests were conducted on samples from KSH01A at the HUT Laboratory /Eloranta 2004c/.

The indirect tensile tests are similar to the Brazilian test but were conducted using curved applicators. Also in this case, some of the samples contained sealed fractures and their results are kept separated from the rest on intact fine-grained dioritoid and quartz monzonite to monzodiorite. The frequency distributions of the indirect tensile strength are shown in Figure 2-5 for the two rock types. The results from /Eloranta 2004c/ on 10 quartz monzonite samples gave a mean value of 15.4 MPa, slightly lower than the results summarised in Table 2-4.

The mean value of the tensile strength TS of the fine-grained dioritoid shows a value similar to that of the Hoek & Brown's Criterion in Figure 2-3. On the other hand, the indirect mean tensile strength does not match the tensile strength estimated by the Hoek & Brown's Criterion very well. This is probably due to the fact that: i) the experimental values are "indirect" tensile strength, thus somehow affected by the loading conditions; ii) the Hoek & Brown's Criterion only approximates the real rock strength envelope for the quartz monzonite to monzodiorite. However, the results of the Hoek & Brown's Criterion are more conservative than the experimental results.

Table 2-4. Summary of the results of indirect tensile tests performed on intact rock samples from borehole KSH01A and KSH02A.

Rock type	Number of samples	Minimum TS [MPa]	Mean TS [MPa]	Frequent TS MPa]	Maximum TS [MPa]	TS Standard deviation [MPa]
Fine-grained dioritoid (metavolcanite, volcanite).	24	14	19	19	24	2
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	18	12	18	17	24	4
All intact rock samples.	42	12	19	19	24	3
Sealed fractures in intact rock.	10	9	14	15	22	5
All samples and sealed fractures.	52	9	18	19	24	4

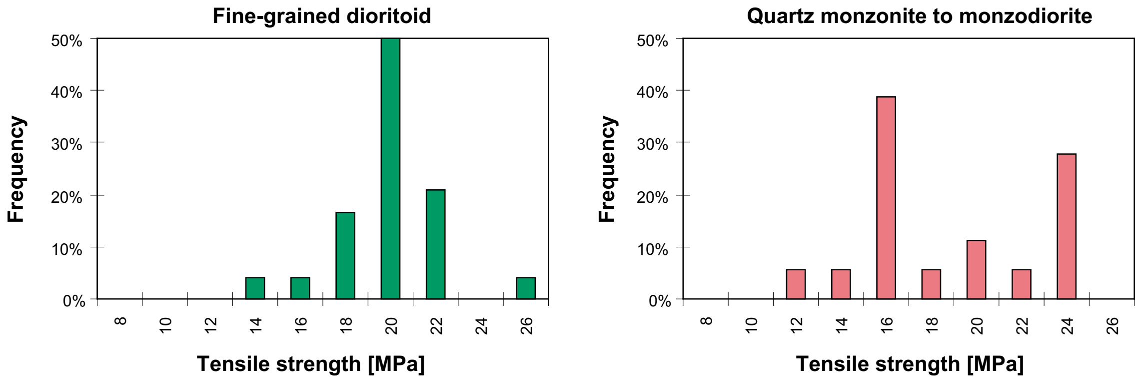


Figure 2-5. *Frequency distribution of the tensile strength of the samples of fine-grained dioritoid and quartz monzonite to monzonite.*

2.4 Young's modulus

The uniaxial and triaxial compressive tests, in addition to the strength, also provide the deformability of the intact rock samples. The deformability is quantified by means of the elastic parameters Young's modulus and Poisson's ratio. Due to the fact that the loading conditions considered are two and for reasons of engineering practice, two sets of Young's modulus and Poisson's ratio are presented here, for uniaxial and triaxial loading conditions, respectively.

2.4.1 Uniaxial loading

The Young's modulus obtained from uniaxial loading (E) is often used in practice for the ease of determination. In Table 2-5, the statistics of the Young's modulus of the intact rock samples of fine-grained dioritoid and quartz monzonite to monzodiorite are summarised /Jacobsson 2004ab/. It is interesting to notice that, independently of the rock type and of the presence of sealed fractures, the Young's modulus of the samples is rather high and the values are very consistent. The comparison between the new test results and the data available from Clab (only four samples) show the same high mean Young's modulus (Figure 2-6).

The results at HUT /Eloranta 2004a/ gave an average Young's modulus of 70 GPa. This result, obtained based on five samples, does not completely agree with Table 2-5, probably due the way the deformations were measured.

2.4.2 Triaxial loading

Also the triaxial deformation modulus (E_{TX}) could be determined from the results by /Jacobsson 2004cd/. This applies for stresses comparable with the once used in the triaxial tests (between 2 and 10 MPa). Considering that the number of samples is rather limited, the triaxial values of the Young's modulus exhibit the same range of variation as the uniaxial Young's modulus. The two sets of parameters could then be considered to represent the same physical property of the intact rock. In Figure 2-7, the frequency distribution of the uniaxial and triaxial Young's modulus is plotted together for comparison. The two distributions appear to almost coincide.

Table 2-5. Summary of the results of Young's modulus from uniaxial compressive tests performed on intact rock samples from borehole KSH01A and KSH02A.

Rock type	Number of samples	Minimum E [GPa]	Mean E [GPa]	Frequent E [GPa]	Maximum E [GPa]	E Standard deviation [GPa]
Fine-grained dioritoid (metavolcanite, volcanite).	10	78	85	83	101	7
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	10	69	78	81	86	7
All intact rock samples.	20	69	82	81	101	7
Fine-grained dioritoid with sealed fractures.	4	83	91	89	104	10
All samples and sealed fractures.	24	69	83	83	104	8

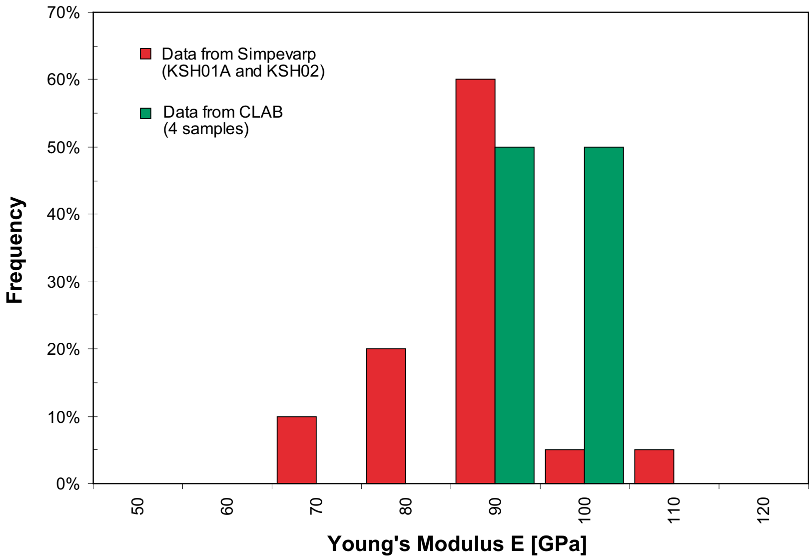


***Figure 2-6.** Comparison of the frequency distributions of the Young's modulus from all uniaxial tests for Simpevarp 1.2 and Clab.*

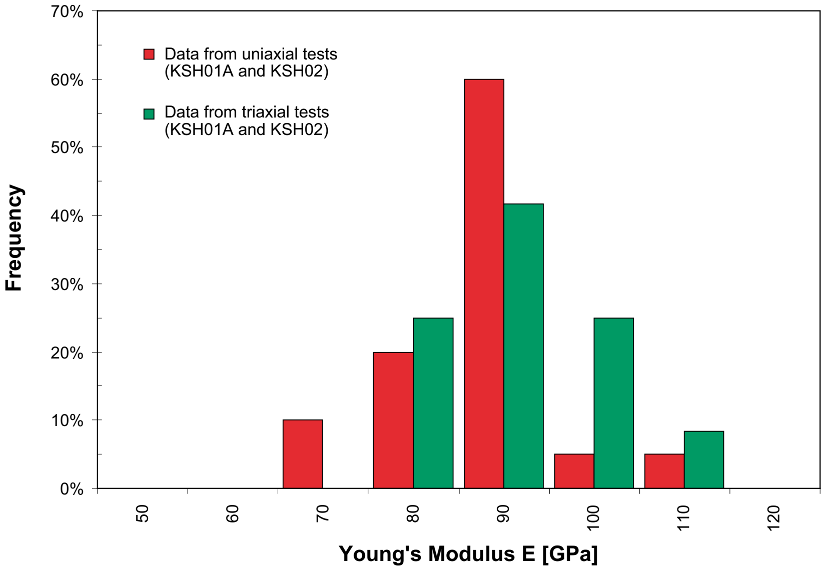


***Figure 2-7.** Comparison of the frequency distributions of the Young's modulus from uniaxial and triaxial tests for Simpevarp 1.2.*

Table 2-6. Summary of the results of Young's modulus from triaxial compressive tests performed on intact rock samples from borehole KSH01A and KSH02.

Rock type	Number of samples	Minimum E_{TX} [GPa]	Mean E_{TX} [GPa]	Frequent E_{TX} [GPa]	Maximum E_{TX} [GPa]	E_{TX} Standard deviation [GPa]
Fine-grained dioritoid (metavolcanite, volcanite).	6	69	78	79	87	6
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	6	69	77	77	91	8
All intact rock samples.	12	69	78	78	91	7
Sealed fractures.	5	75	81	83	88	5
All samples and sealed fractures.	17	69	79	78	91	6

2.5 Poisson's ratio

As for the Young's modulus, also the Poisson's ratio can be obtained from uniaxial and triaxial tests.

2.5.1 Uniaxial loading

Table 2-7 shows the summary of the values of Poisson's ratio (ν) determined from uniaxial compressive tests on intact rock samples /Jacobsson 2004ab/. Also the Poisson's ratio of the fine-grained dioritoid and quartz monzonite to monzodiorite are very similar to each other. Only the samples exhibiting sealed fractures show slightly lower values. In Figure 2-8, the only available value from the testing for the construction of the Clab facility seems to match the new experimental results very well.

The Poisson's ratio for the quartz monzonite obtained at HUT /Eloranta 2004a/, on average 0.32, is much larger than the values in Table 2-7.

Table 2-7. Summary of the results of Poisson's ratio from uniaxial compressive tests performed on intact rock samples from borehole KSH01A and KSH02A.

Rock type	Number of samples	Minimum ν [–]	Mean ν [–]	Frequent ν [–]	Maximum ν [–]	ν Standard deviation [–]
Fine-grained dioritoid (metavolcanite, volcanite).	10	0.21	0.26	0.26	0.31	0.03
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	10	0.19	0.27	0.28	0.33	0.05
All intact rock samples.	20	0.19	0.27	0.27	0.33	0.04
Fine-grained dioritoid with sealed fractures.	4	0.18	0.24	0.24	0.31	0.07
All samples and sealed fractures.	24	0.18	0.26	0.27	0.33	0.04

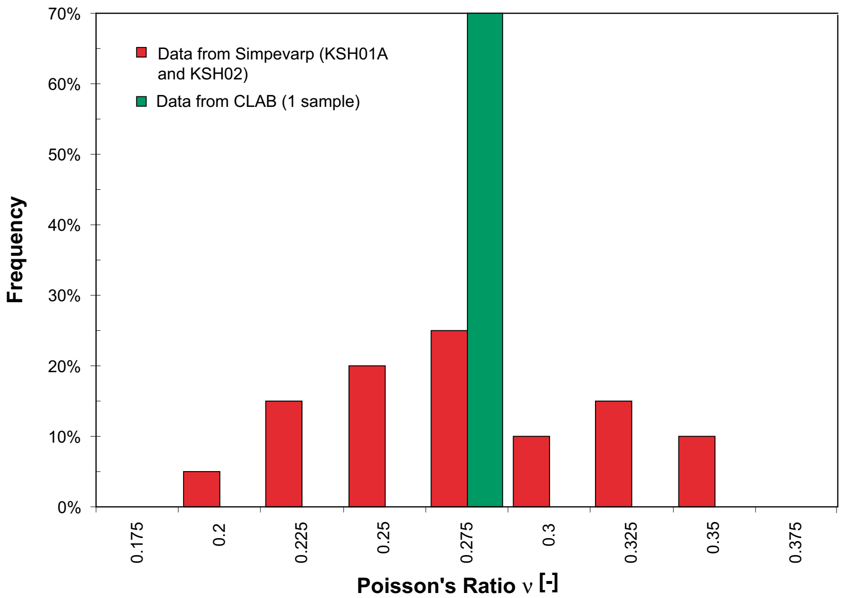


Figure 2-8. Comparison of the frequency distributions of the Poisson's ratio from all uniaxial tests for Simpevarp 1.2 and Clab.

2.5.2 Triaxial loading

The summary of the statistics of the Poisson's ratio from triaxial tests ν_{TX} is presented in Table 2-8 /Jacobsson 2004cd/. These values differ from those from uniaxial tests and are in general lower (22–24%). This is certainly the effect of the lateral confinement that limits the lateral expansion of the samples and produces lower Poisson's ratios. It is possible that, for larger confinement stresses than 10 MPa, even lower Poisson's ratio can be observed in laboratory. The data from uniaxial and triaxial tests can be compared as in Figure 2-9. As observed before, the triaxial values are smaller than the uniaxial Poisson's ratio values.

Table 2-8. Summary of the results of Poisson's ratio from triaxial compressive tests performed on intact rock samples from borehole KSH01A and KSH02A.

Rock type	Number of samples	Minimum ν_{TX} [–]	Mean ν_{TX} [–]	Frequent ν_{TX} [–]	Maximum ν_{TX} [–]	ν_{TX} Standard deviation [–]
Fine-grained dioritoid (metavolcanite, volcanite).	6	0.19	0.21	0.20	0.23	0.02
Quartz monzonite to monzodiorite (equigranular to weakly porphyritic).	6	0.18	0.22	0.23	0.24	0.02
All intact rock samples.	12	0.18	0.21	0.22	0.24	0.02
Sealed fractures.	5	0.15	0.18	0.18	0.24	0.03
All samples and sealed fractures.	17	0.15	0.20	0.20	0.24	0.03

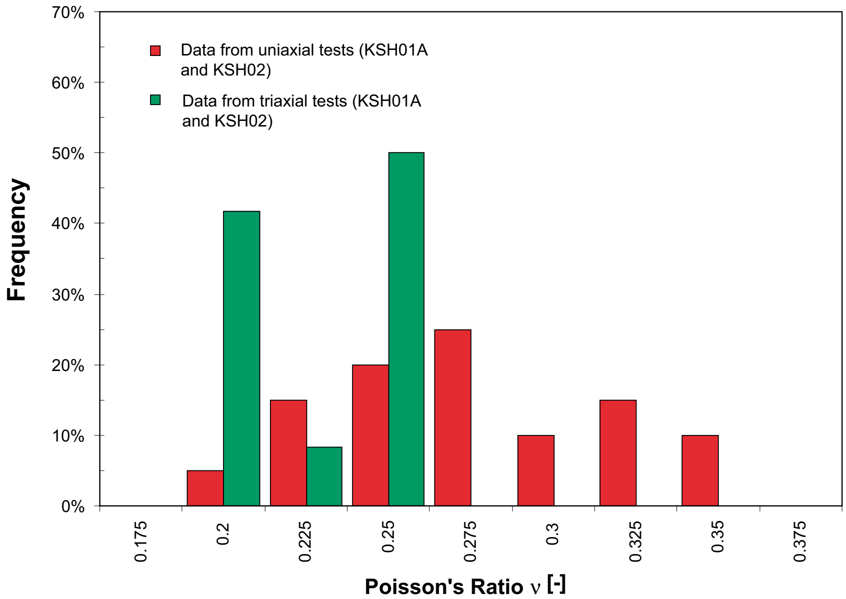


Figure 2-9. Comparison of the frequency distributions of the Poisson's ratio from uniaxial and triaxial tests for Simpevarp 1.2.

3 Rock fractures

The strength and deformability of the natural rock fractures can basically be tested in two ways:

1) By mean of tilt test where shearing is induced by the self-weight of the upper block when the fracture is progressively tilted;
2) By means of direct shear tests where shearing is induced by actuators that apply a load perpendicular and parallel to the fracture plane.

Tilt tests were performed on samples from borehole KSH01A, KSH02A, KAV01 and KLX02. Direct shear tests were performed by two different laboratories on fractures from borehole KSH01A (the Norwegian Geological Institute Laboratory, NGI) and from borehole KSH01A, KSH02A, KAV01 (the SP Laboratory). In the following sections, a summary of the fracture strength results is provided.

3.1 Tilt tests

Tilt tests were carried out on 142 samples from borehole KSH01A, KSH02A, KAV01 and KLX02 /Chryssanthakis 2003, 2004a–c/. The tilt tests are designed to suit the fracture parameter determination according to /Barton and Bandis 1990/. The shear strength of the fracture is a function of the normal stress σ_n as:

$$\tau = \sigma_n \tan\left[\Phi_b + JRC \log\left(\frac{JCS}{\sigma_n}\right)\right] \qquad (2)$$

JRC is Joint Roughness Coefficient that quantifies roughness, JCS is Joint Wall Compression Strength of the rock surfaces, and Φ_b is basic friction angle on dry saw-cut surfaces. The residual friction angle Φ_r is used instead of Φ_b if the strength of wet surfaces is concerned. /Barton and Bandis 1990/ also suggest a truncation of the strength envelope for low normal stresses as follows: τ/σ should always be smaller than 70° and in this case the envelope should go through the origin ($\sigma_n = \tau = 0$ MPa).

The parameters of the Barton and Bandis's Criterion are summarised in Table 3-1 for each borehole and for all the fractures. In Table 3-2, the samples are grouped into fracture sets according to the DFN model for the Site /Hermansson et al. 2005/. It can be observed that, independently on the fracture orientation and borehole, the fracture parameters do not noticeably change.

When a certain level of stresses is decided, the relation in Equation (2) can be linearly approximated so that friction angle and cohesion of the Coulomb's Strength Criterion can be determined.

Table 3-1. Summary of the results of tilt tests performed on rock fractures samples from borehole KSH01A, KSH02, KAV01 and KLX02 /Chryssanthakis 2003, 2004a–c/.

Borehole	Number of samples	Basic friction angle [°]	JRC0 (100 mm)	JCS0 (100 mm)	Residual friction angle [°]
KSH01A	51	31.3 (2.4)	6.0 (1.1)	79.4 (27.4)	26.8 (3.4)
KSH02	48	31.5 (1.6)	5.8 (1.4)	70.3 (25.7)	26.2 (3.4)
KAV01	26	30.8 (0.8)	6.2 (1.6)	53.0 (13.2)	26.3 (2.2)
KLX02	24	31.4 (1.2)	6.7 (1.5)	63.3 (21.4)	25.44 (3.4)
All fractures	149	31.3 (1.8)	6.1 (1.4)	62.7 (25.5)	26.3 (3.1)

The average values are indicated with the standard deviation between brackets.

Table 3-2. Summary of the results of tilt tests performed on rock fractures grouped in different fracture sets. Smaples from borehole KSH01A, KSH02, KAV01 and KLX02 /Chryssanthakis 2003, 2004a–c/.

Fracture set	Number of samples	Basic friction angle [°]	JRC0 (100 mm)	JCS0 (100 mm)	Residual friction angle [°]
NS	3	31.2 (0.9)	5.8 (1.4)	95.4 (15.1)	28.6 (1.0)
NNE	6	31.8 (1.8)	6.6 (1.7)	56.6 (24.0)	26.5 (4.2)
NE	7	31.7 (1.0)	5.7 (1.2)	86.8 (36.2)	27.6 (2.9)
ENE	5	30.0 (3.3)	6.8 (1.4)	76.8 (32.2)	26.5 (3.3)
EW	4	31.5 (2.3)	6.6 (0.8)	60.5 (7.8)	25.6 (3.3)
WNW	6	31.1 (1.8)	6.2 (1.9)	64.9 (20.2)	26.7 (3.7)
NW	6	31.2 (1.2)	5.8 (0.9)	66.2 (25.9)	25.5 (1.4)
NNW	6	30.9 (1.0)	5.9 (2.3)	74.5 (15.0)	25.8 (2.6)
SubH	43	31.8 (1.5)	5.6 (1.3)	68.6 (27.6)	26.9 (3.6)
Random	55	31.1 (2.1)	6.4 (1.3)	68.5 (24.8)	25.8 (3.0)
Sealed	7	30.5 (1.1)	6.3 (1.0)	66.4 (19.8)	26.1 (2.4)
All fractures	149	31.3 (1.8)	6.1 (1.4)	62.7 (25.5)	26.3 (3.1)

The average values are indicated with the standard deviation between brackets.

3.2 Direct shear tests

Since two sets of data were tested at two different laboratories, these results are presented separately and then compared.

3.2.1 NGI Laboratory results

Seven samples from borehole KSH01A were tested at the NGI Laboratory /Chryssanthakis 2004d/. The fractures could be identified and assigned to the fracture sets at the Site /Hermansson et al. 2005/. Some of the tested samples were partially sealed or mineral infilled. Tests were performed with 0.5, 5 and 20 MPa normal stress. The mean value obtained from all the samples is quite similar to the results obtained for individual fracture sets (Table 3-3). Thus, the fractures could be grouped all together. In this way, the peak and residual parameters could be determined with maximum and minimum ranges for all tested fractures (Table 3-4).

Table 3-3. Peak and residual friction angle and cohesion for Coulomb's Criterion from the tests on samples from borehole KSH01A (NGI Laboratory results).

Fracture set	Number of samples/tests	Peak friction angle [°]	Peak cohesion [MPa]	Residual friction angle [°]	Residual cohesion [MPa]
NE	2/6	35.3	1.3	35.0	0.6
EW	1/3	30.1	0.9	30.4	0.6
SubH	1/3	38.5	1.0	37.7	0.4
Sealed	3/6	33.5	1.3	32.6	0.6
All fractures	7/18	34.4 (3.0)	1.2 (0.2)	34.0 (2.7)	0.6 (0.1)

The average values are indicated with the standard deviation between brackets.

Table 3-4. Minimum, mean and maximum envelopes on friction angle and cohesion for Coulomb's Criterion for all tests on samples from borehole KSH01A (NGI Laboratory results).

	Minimum friction angle [°]	cohesion [MPa]	Mean friction angle [°]	cohesion [MPa]	Maximum friction angle [°]	cohesion [MPa]
Peak envelope	31.9	0.4	34.5	1.2	36.9	1.9
Residual envelope	31.7	–0.1	34.0	0.6	36.1	1.2

3.2.2 SP Laboratory results

28 natural fractures from borehole KSH01A, KSH02A and KAV01 were tested at the SP Laboratory /Jacobsson 2004g–i/. Normal loading tests were carried out with normal stress up to 10 MPa. Direct shear tests were performed on the fractures at the different normal stress levels: 0.5, 5 and 20 MPa. From the tests, the experimental peak and residual envelopes were evaluated to determine the strength parameters. Deformability parameters could be obtained from the stress-displacement curves.

Deformability

The secant normal stiffness of the fracture samples for normal stress between 0.5 and 10 MPa was evaluated for the second loading cycle as in Figure 3-2 (left). The shear stiffness was determined as the secant stiffness between a shear stress of 0 MPa and half of the peak shear stress (Figure 3-2, right). The maximum, mean, minimum and standard deviation values of the secant normal and shear stiffness of all the samples are summarised in Table 3-5.

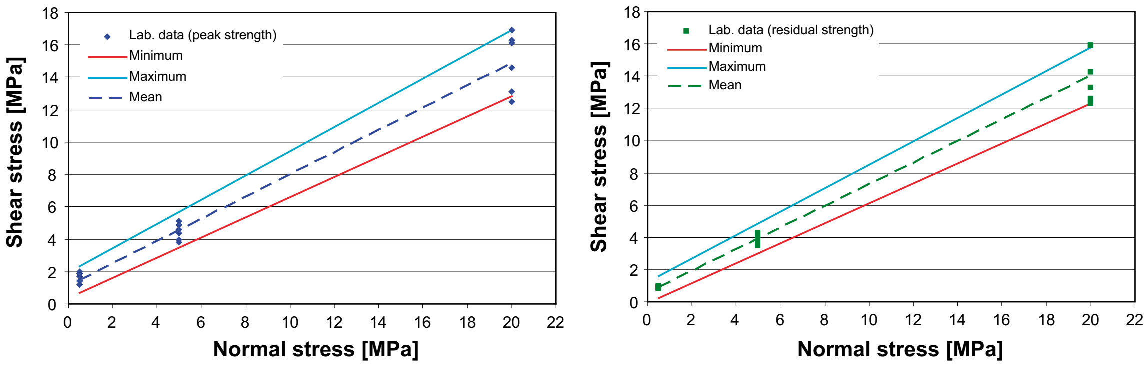


Figure 3-1. *Peak (left) and residual (right) shear strength according to Coulomb's Criterion for all fracture samples from borehole KSH01A (NGI Laboratory results).*

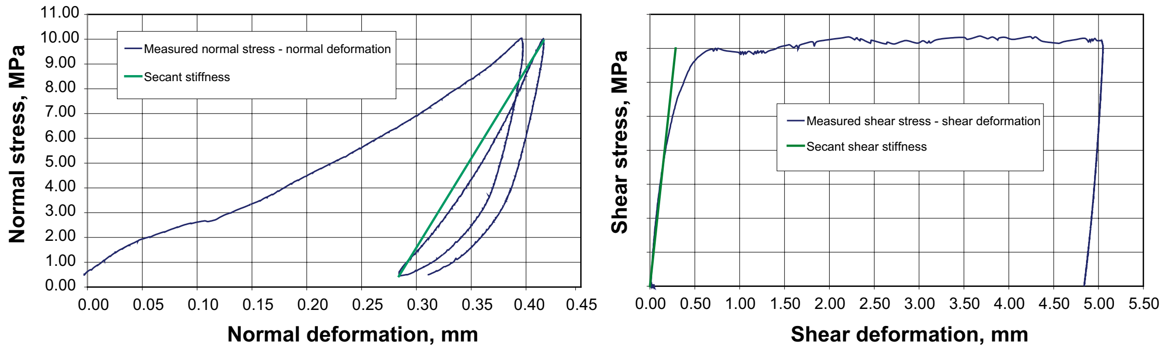


Figure 3-2. *Example of evaluation of the secant normal stiffness (left – second loading cycle) and shear stiffness (right) (SP Laboratory results).*

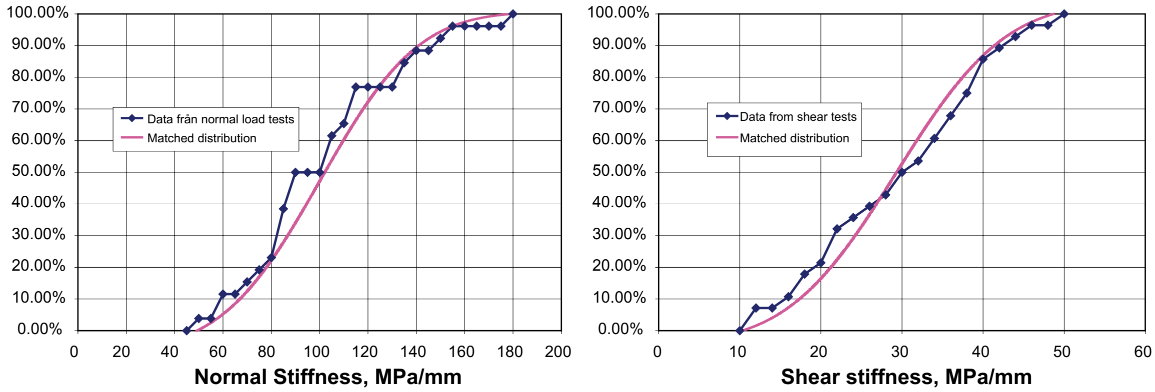


Figure 3-3. *Cumulative distribution of the normal stiffness (left) and shear stiffness (right) for all the tested natural fracture samples from borehole KSH01A, KSH02A and KAV01 (SP Laboratory results).*

Table 3-5. Minimum, mean and maximum normal and shear stiffness for all the tested fracture samples from borehole KSH01A, KSH02A and KAV01 (SP Laboratory results).

	Minimum		Mean		Maximum		Standard deviation	
	Normal stiffness [GPa/mm]	Shear stiffness [GPa/mm]	Normal stiffness [GPa/mm]	Shear stiffness [GPa/mm]	Normal stiffness [GPa/mm]	Shear stiffness [GPa/mm]	Normal stiffness [GPa/mm]	Shear stiffness [GPa/mm]
All samples	49.2	10.3	100.2	29.3	179.3	48.7	31.9	10.6

Strength

The statistical distributions of the peak fracture cohesion and friction angle according to the Coulomb's Strength Criterion are shown in Figure 3-4. Table 3-6 summarises the statistics of the peak fracture cohesion and friction angle of all the samples of natural fractures tested at the SP Laboratory.

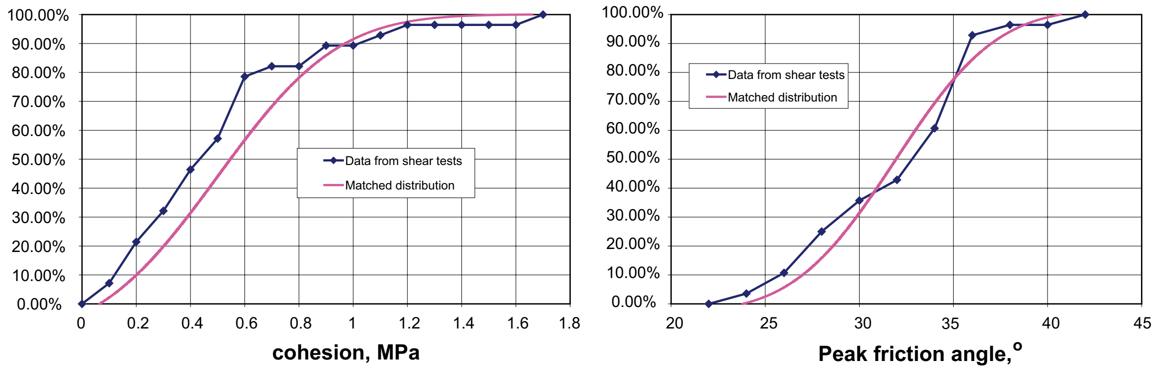


Figure 3-4. *Cumulative distribution of the peak fracture cohesion (left) and peak friction angle (right) for the samples from borehole KSH01A, KSH02A and KAV01 (SP Laboratory results).*

Table 3-6. Minimum, mean and maximum envelopes of the friction angle and cohesion for the Coulomb's Criterion. All tests on natural fracture samples from borehole KSH01A, KSH02A and KAV01 are considered (SP Laboratory results).

Peak envelope	Minimum friction angle [°]	cohesion [MPa]	Mean friction angle [°]	cohesion [MPa]	Maximum friction angle [°]	cohesion [MPa]	Standard deviation friction angle [°]	cohesion [MPa]
All samples	23.8	0.07	31.9	0.50	40.7	1.66	4.3	0.35

3.3 Comparison of the laboratory results on fractures

The statistical parameters obtained from the three different sets of tests on natural fractures are compared in Table 3-7. The different testing techniques and the number of tested samples for each set of results justify the slight spread of the results. However, it was decided to give more weight to the largest set of results of direct shear tests.

Table 3-7. Comparison of the mean and standard deviation of the peak cohesion and friction angle obtained from different testing techniques and laboratories.

Laboratory test results	Number of samples	Mean peak friction angle [°]	Standard deviation peak friction angle [°]	Mean peak cohesion [MPa]	Standard deviation peak cohesion [MPa]
Direct shear test – SP Laboratory KSH01A, KSH02A, KAV01.	28	31.9	4.3	0.5	0.35
Direct shear test – NGI Laboratory KSH01A.	6 (1 sealed neglected)	34	3.5	1.2	0.2
Tilt test* KSH01A, KSH02, KAV01 and KLX02.	142 (7 sealed neglected)	34	3.5	0.4	0.1

* The values reported here are obtained from the Barton-Bandis' Criterion for normal stresses between 0.5 and 20 MPa.

The presence of correlation between the peak cohesion and friction angle of the natural fractures was also investigated for the different sets of results. In Figure 3-5, all the analyzed results are shown. Some correlation can be noticed for the results of direct shear testing from the SP Laboratory. This correlation is not supported by the data from NGI Laboratory and from the Barton-Bandis' Criterion applied to the tilt test results. However, the correlation for the SP results is assumed as a "work hypothesis" that should be checked as soon as more laboratory results from other boreholes at the Site will be available.

The suggested correlation between the peak cohesion and friction angle of the natural fractures at Simpevarp has been summarized in Table 3-8. The minimum and maximum values of the peak cohesion as a function of the peak friction angle are also shown Figure 3-5 (right). The minimum and maximum fitting lines are empirically chosen.

The basic friction angle, which can be assimilated to the frictional strength of rock saw-cut surfaces, can be used to determine the dilation angle, which quantifies the frictional effect of the asperities of the fracture walls. The difference between the peak friction angle and the basic friction angle can be used as a measure of the dilation angle in peak strength conditions.

Table 3-8. Minimum, mean, maximum and standard deviation of the cohesion as a function of the friction angle φ' assumed for all fracture sets at Simpevarp.

All fracture sets	Minimum	Mean/Standard deviation	Maximum
Peak friction angle φ' [°]	24°	32°/4°	40°
Peak cohesion c' [MPa]	[1.98–0.058 φ'] MPa	[2.35 - 0.058 φ'] MPa/0.25 MPa	[3.04–0.058 φ'] MPa

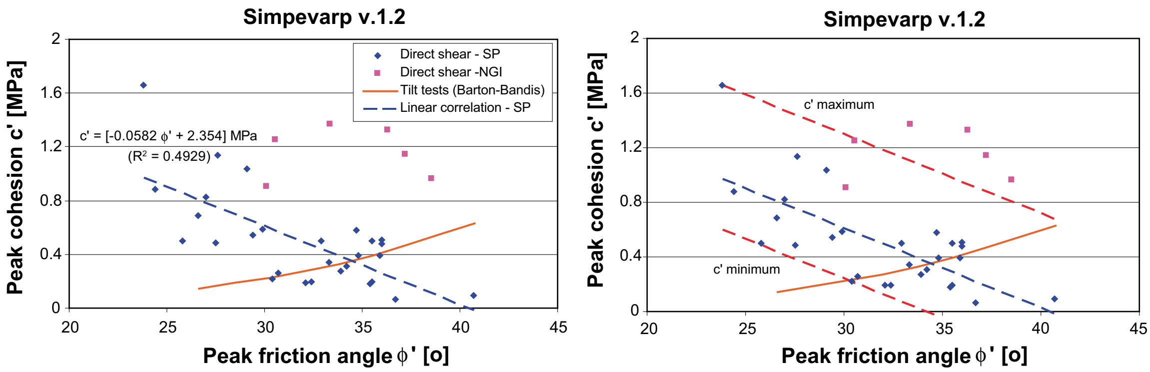


Figure 3-5. Correlation between the peak cohesion and friction angle obtained with different testing techniques and sample sets.

4 Conclusions

Laboratory tests were performed on intact rock and natural fracture samples taken from the boreholes at the Simpevarp Site. Intact rock samples were selected to represent some of the dominant rock types, which are fine-grained dioritoid and quartz monzonite to monzodiorite. The samples were collected from boreholes KSH01A and KSH02A.

Intact rock samples were tested in uniaxial, triaxial and tensile conditions. Based on the tests results, the strength parameters of the intact rock were determined: i) the uniaxial compressive strength; ii) the Hoek & Brown's strength parameters and; iii) the Coulomb's strength parameters (apparent friction angle and cohesion). The uniaxial compressive strengths of two rock types are rather different. The dioritoid has an average uniaxial strength of about 205 MPa while the monzonite has a uniaxial strength of about 161 MPa. The minimum observed values are almost the same for the two rock types (about 110 MPa). On the other hand, as expected, the maximum observed strength for the quartz monzonite is 195 MPa and for fine-grained dioritoid is 265 MPa, respectively.

From the triaxial compressive tests of the intact rock samples, the Hoek & Brown's Criterions' parameters can be determined. These give an approximated value of the uniaxial compressive strength that suits the results at larger confining stresses. These values are very close to those obtained from uniaxial compressive strength. Moreover, the parameter m_i, typical of each rock type, is also determined. m_i is around a value of 14 for the dioritoid and 31 for the monzonite, respectively. The Hoek & Brown's Criterion can be approximated by the Coulomb's Criterion within the same range of stress used for the triaxial testing. This approximation returns the cohesion and friction angle of the intact rock for stresses between 0 and 15 MPa. The cohesion of the quartz monzonite (about 20 MPa) is lower than that of the dioritoid (about 33 MPa). The spreading of these values is within a range of about ±20% around the mean for the quartz monzonite and about ±43% for the dioritoid, respectively. Also the friction angles for the two rock types are different: the dioritoid has lower friction angle (53°) than the monzonite (60°). The friction angle of the monzonite may vary within ±1% around the mean, while that of the dioritoid varies in a wider range, approximately ±3%.

Indirect tensile tests were conducted on the core samples in a fashion very similar to the Brazilian test. The two rock types exhibited almost the same tensile strength (around 18–19 MPa) and the same scatter of the values of about ±33%. The values of the tensile strength obtained experimentally do not match well the Hoek & Brown's Criterion. The difference is largest for the quartz monzonite. This might be explained by the fact that: i) the Hoek & Brown's Criterion is an empirical approximation of the experimental results, and applies best to uniaxial and triaxial conditions; ii) the tensile strength determined in the laboratory is "indirect", and the method might overestimate the tensile strength.

The compression tests also provide the deformational properties of the intact rock by means of the Young's modulus and Poisson's ratio. The Young's modulus of the intact rock from uniaxial compression tests is 85 GPa for the fine-grained dioritoid and 78 GPa for the monzonite, respectively. The experimental values range within ±9% around the mean values. The Young's modulus from triaxial tests is lower for the dioritoid (78 GPa) but unchanged for the monzonite. The Poisson's ratio can also be determined from the experiment under uniaxial and triaxial conditions. In uniaxial conditions, the Poisson's ratio of the dioritoid is 0.26 and that of the monzonite is 0.27. The experimental values are scattered in a range of up to 20% of the mean and around the mean value. In triaxial conditions, the Poisson's ratio of the two rock types diminishes to about 19%, and its scatter reduces to about ± 9%.

Samples of natural fractures were tested to determine strength and deformability. Tilt, normal load and direct shear test results were available for samples from four boreholes (KSH01A, KSH02A, KLX02 and KAV01). The comparison of the results at the Site shows that there should not be any appreciable differences between the parameters of the different fracture sets. Thus, all statistics of the parameters are calculated on the results as a whole. In some cases, the orientation of the fractures was not available, so the grouping into fracture sets was not possible.

The tilt tests return the values of basic friction angle, the Joint Roughness Coefficient JRC_0, the Joint wall Compressive Strength JCS_0, and the residual friction angle. On average, the basic friction angle is 31° (standard deviation 1.8°) and the residual friction angle 26° (wet). The mean JRC_0 is around 6 while the JCS_0 is around 63 MPa. These parameters can be used to extrapolate the strength of the samples to higher normal stresses than for the tilt tests. Thus, the peak friction angle and peak cohesion can be estimated for a normal stress range between 0.5 and 20 MPa. These are calculated in 34° and 0.37 MPa, respectively.

Direct shear testing was performed by two different laboratories (NGI and SP) on different sets of samples. The two sets of results differ somewhat for the number of tests and the range of results obtained. The NGI Laboratory tested seven samples from only one borehole. They obtained an average peak friction angle of 34° and peak cohesion of 1.2 MPa. The SP Laboratory tested other samples from three boreholes, one of which was the same as for the former set of data. The peak friction angle from SP's tests was on average 32° and the peak cohesion 0.5 MPa. Besides the strength, also the deformability of the fractures could be determined from the tests. The normal stiffness of the fractures (secant; normal stresses between 0 and 10 MPa) was on average 100 MPa/mm while the shear stiffness was about 30 MPa/mm (secant; normal stresses between 0.5 and 20 MPa).

The data from the SP Laboratory were much more numerous than those from the NGI Laboratory. Furthermore, the direct shear testing technique was judged more robust than the tilt testing technique. The equipment for direct shear testing also makes it possible to determine the normal and shear stiffness of the fracture samples. For these reasons, direct shear testing from the SP Laboratory were given more credit and were used to quantify strength and deformability of the natural fractures at the Simpevarp Site.

The correlation between the data on peak cohesion and friction angle was also studied. In fact, the presence of correlation between these two parameters would allow a reduction of the number of independent parameters that describe the mechanical properties of the fractures and, thus, of the rock mass. A weak correlation was observed between cohesion and friction angle in the SP data. This correlation is adopted as a "work hypothesis" for further modelling of the fractures with the reservation that it should be checked against the new data collected in the future at the Simpevarp and Laxemar Sites.

As a first approximation, the dilation angle of the natural fractures in peak strength conditions can be obtained by subtracting the basic friction angle from the peak friction angle obtained from tilt tests. The strength parameters of the natural fractures were also evaluated for residual condition.

The intact rock and natural fracture parameters summarised in this report will be used by the Preliminary Site Descriptive Model for Simpevarp version 1.2 to estimate the mechanical properties of the rock mass for the sake of design and quality assessment evaluations.

5 References

Barton N, Bandis SC, 1990. Review of predictive capabilities of JRC-JCS model in engineering practice, Proc. Int. Symp. Rock Joints, Loen, Norway (eds. Barton N & Stephansson O), Balkema: Rotterdam, p. 603-10.

Chryssanthakis P, 2003. Oskarshamn Site Investigation – borehole KSH01A, Results of tilt testing, SKB P-03-107, Svensk Kärnbränslehantering AB.

Chryssanthakis P, 2004a. Oskarshamn Site Investigation – borehole KSH02, Results of tilt testing, SKB P-04-10, Svensk Kärnbränslehantering AB.

Chryssanthakis P, 2004b. Oskarshamn Site Investigation – borehole KAV01, Results of tilt testing, SKB P-04-42, Svensk Kärnbränslehantering AB.

Chryssanthakis P, 2004c. Oskarshamn Site Investigation – borehole KLX02, Results of tilt testing, SKB P-04-44, Svensk Kärnbränslehantering AB.

Chryssanthakis P, 2004d. Oskarshamn Site Investigation – Drill hole: KSH01A, The normal stress and shear tests on joints, SKB P-04-185, Svensk Kärnbränslehantering AB.

Eloranta P, 2004a. Oskarshamn Site Investigation – Uniaxial compression tests (HUT), SKB P-04-182, Svensk Kärnbränslehantering AB.

Eloranta P, 2004b. Oskarshamn Site Investigation – Triaxial compression tests (HUT), SKB P-04-177, Svensk Kärnbränslehantering AB.

Eloranta P, 2004c. Oskarshamn Site Investigation – Drill hole KSH01A: Indirect tensile strength test (HUT), SKB P-04-184, Svensk Kärnbränslehantering AB.

Hermansson J, Forsberg O, Fox A, La Pointe P, 2005. Statistical model of fractures and deformation zones – Preliminary Site Description, Laxemar subarea version 1.2, SKB R-05-45, Svensk Kärnbränslehantering AB.

Hoek E, Carranza-Torres C, Corkum B, 2002: The Hoek-Brown Failure Criterion – 2002 Edition. 5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada Conference: NARMS-TAC, p. 267–271.

Jacobsson L, 2004a. Oskarshamn Site Investigation – Drill hole KSH01A, Uniaxial compression test on intact rock, SKB P-04-207, Svensk Kärnbränslehantering AB.

Jacobsson L, 2004b. Oskarshamn Site Investigation – Drill hole KSH02A, Uniaxial compression test on intact rock, SKB P-04-209, Svensk Kärnbränslehantering AB.

Jacobsson L, 2004c. Oskarshamn Site Investigation – Drill hole KSH01A, Triaxial compression test on intact rock, SKB P-04-208, Svensk Kärnbränslehantering AB.

Jacobsson L, 2004d. Oskarshamn Site Investigation – borehole KSH02A, Triaxial compression test on intact rock, SKB P-04-210, Svensk Kärnbränslehantering AB.

Jacobsson L, 2004e. Oskarshamn Site Investigation – Drill hole KSH01A, Indirect tensile strength test, SKB P-04-62, Svensk Kärnbränslehantering AB.

Jacobsson L, 2004f. Oskarshamn Site Investigation – Drill hole KSH02, Indirect tensile strength test, SKB P-04-63, Svensk Kärnbränslehantering AB.

Jacobsson L, 2004g. Oskarshamn Site Investigation – Drill hole KSH01A, Normal loading and shear tests on joints, SKB P-05-06, Svensk Kärnbränslehantering AB.

Jacobsson L, 2004h. Oskarshamn Site Investigation – Drill hole KSH02, Normal loading and shear tests on joints, SKB P-05-07, Svensk Kärnbränslehantering AB.

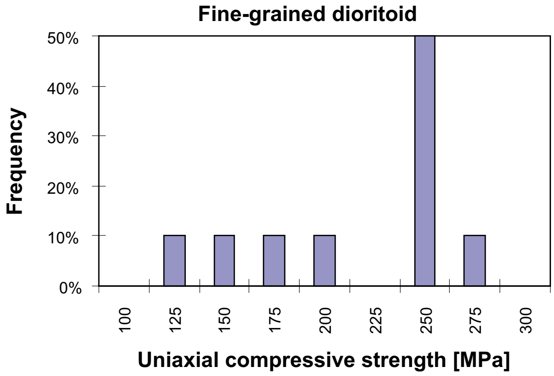
Jacobsson L, 2004i. Oskarshamn Site Investigation – Drill hole KAV01, Normal loading and shear tests on joints, SKB P-05-05, Svensk Kärnbränslehantering AB.

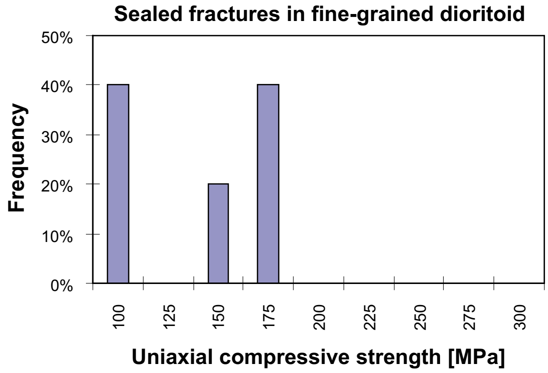
SKB, 2004. Preliminary Site Description. Simpevarp Area – Version 1.1, SKB R-04-25, Svensk Kärnbränslehantering AB.

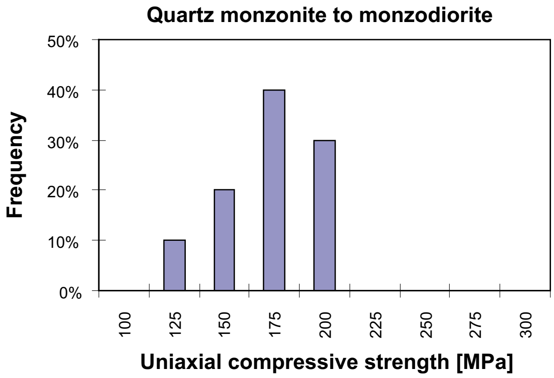
Appendix 1

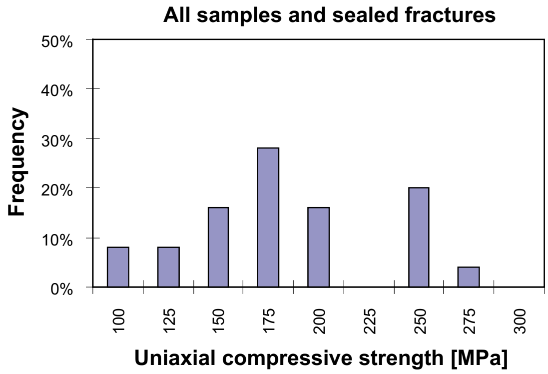
Intact rock

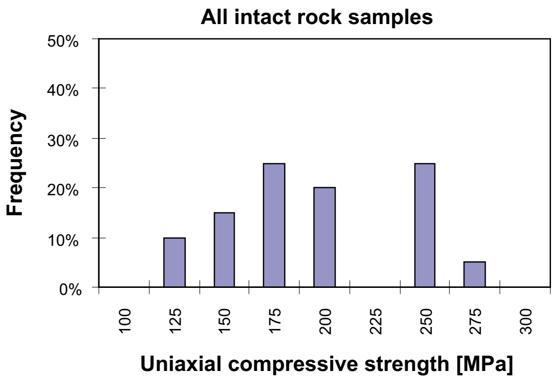
Uniaxial compressive strength (borehole KSH01A and KSH02)



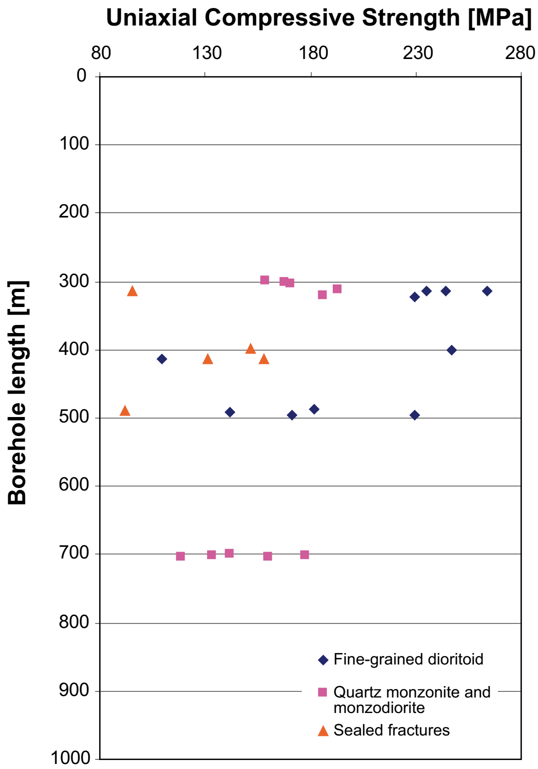


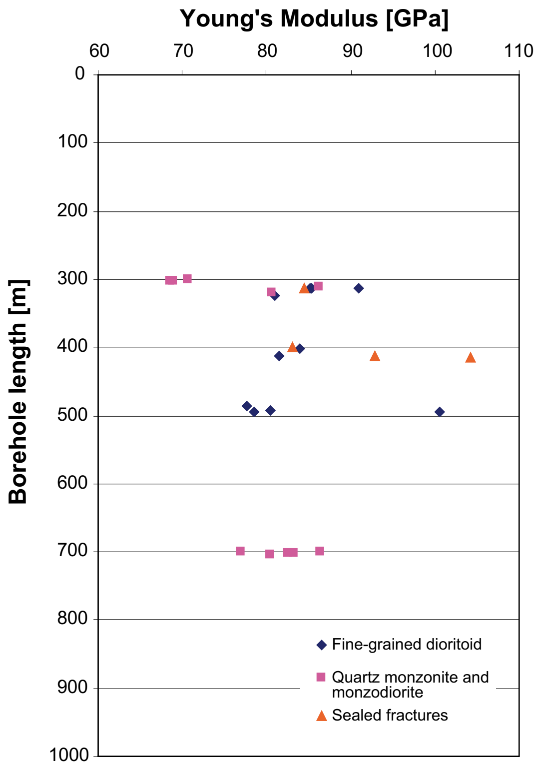


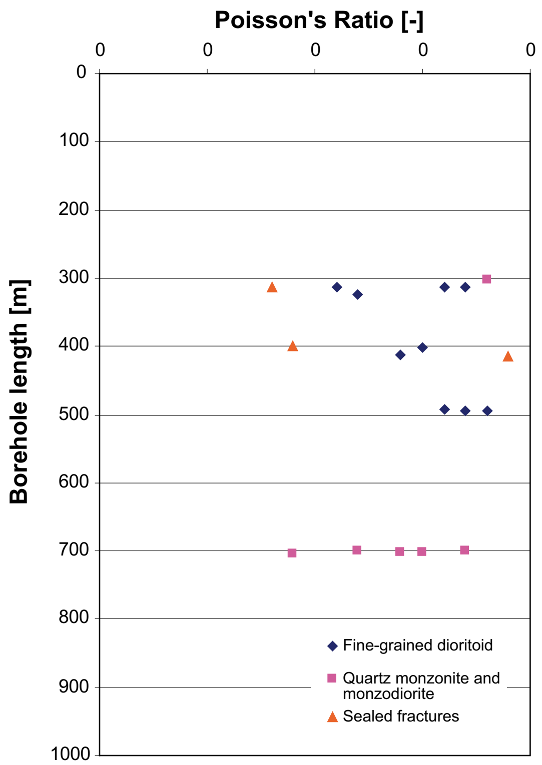




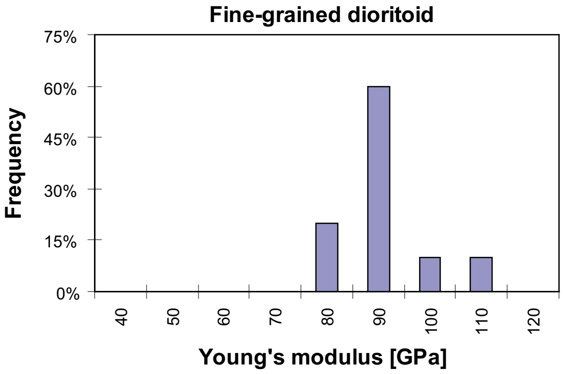
Variation of the uniaxial compressive strength with borehole length

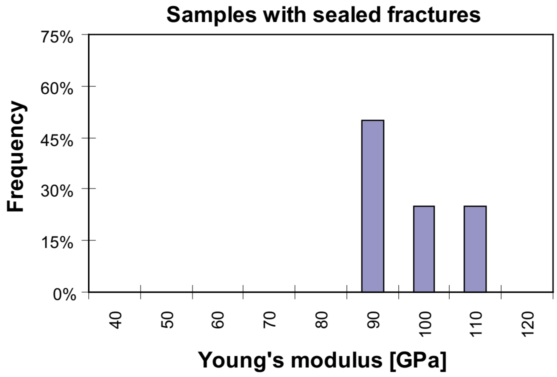


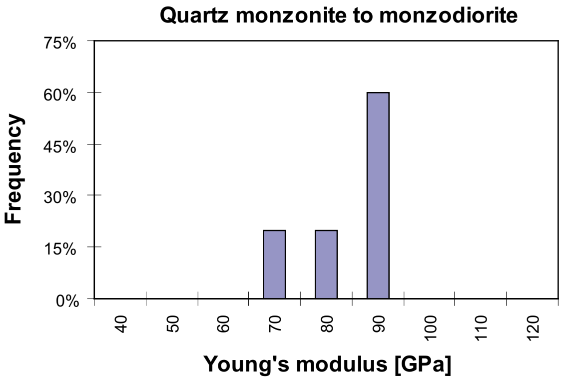


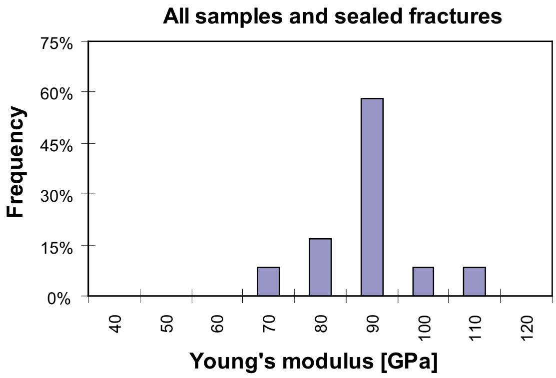


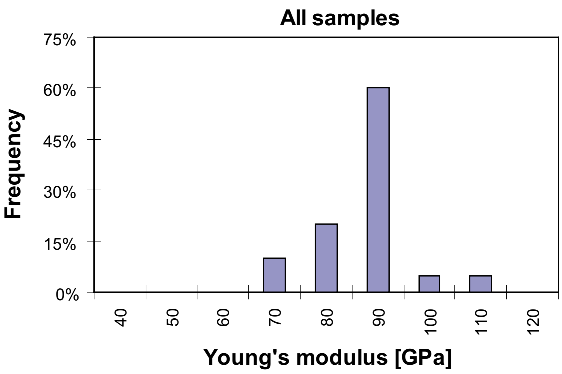
Young’s modulus from uniaxial tests



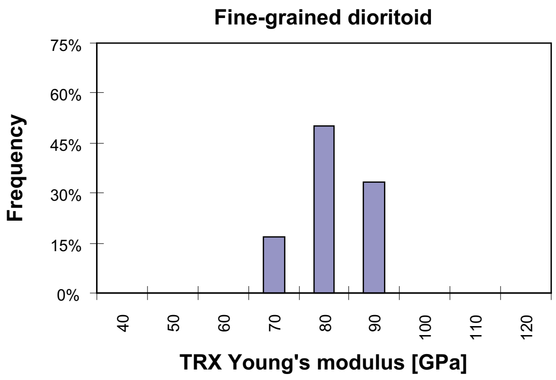


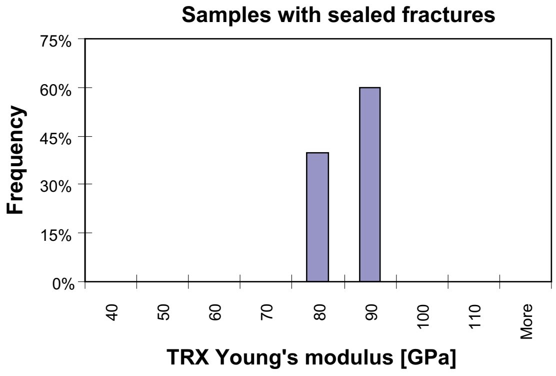


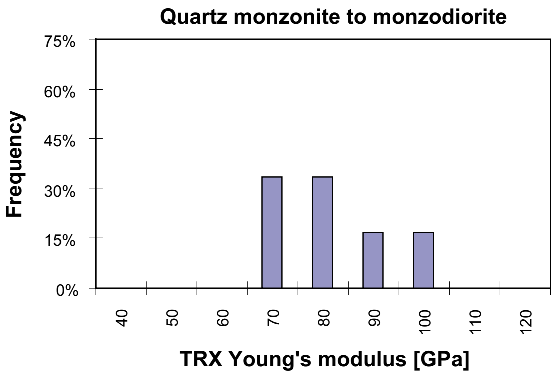


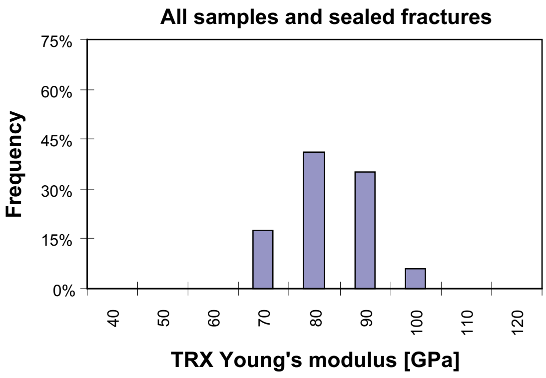


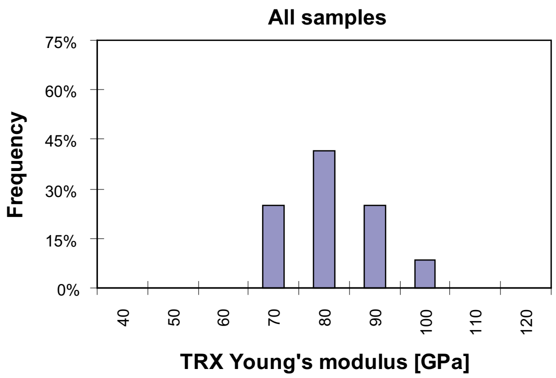
Young’s modulus from triaxial tests



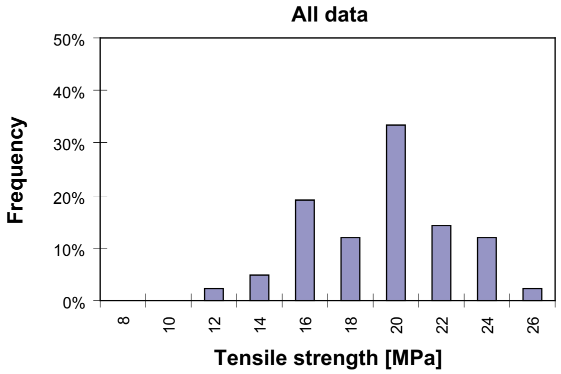


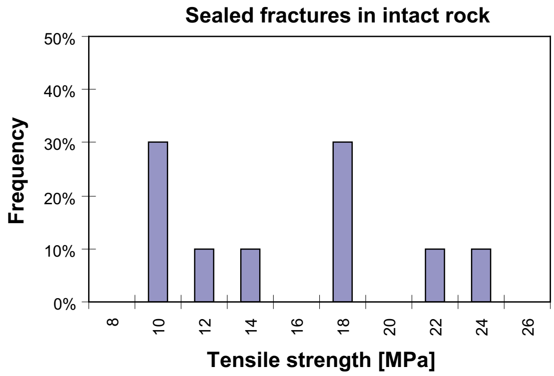


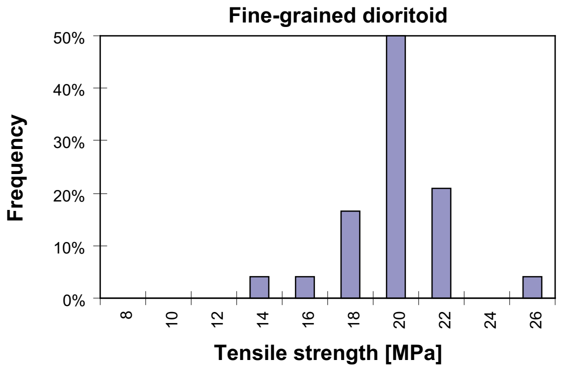


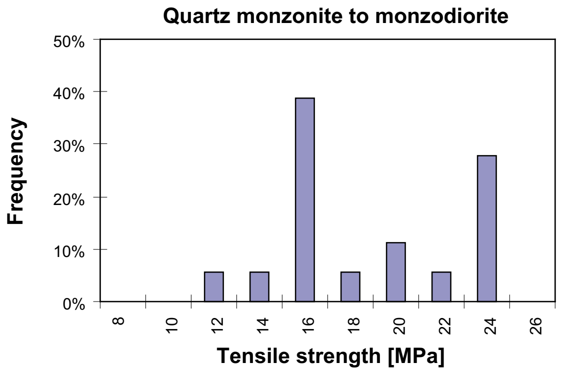


Indirect tensile strength

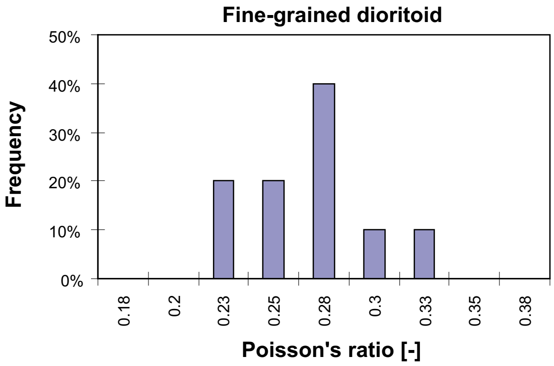


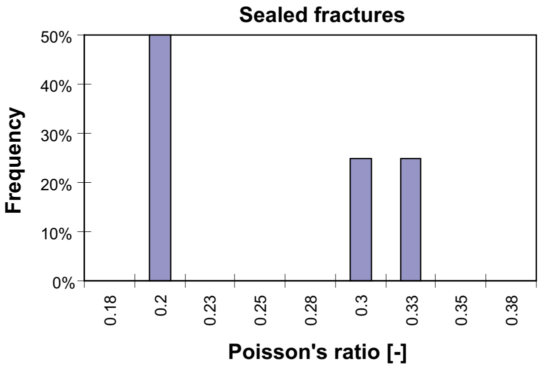


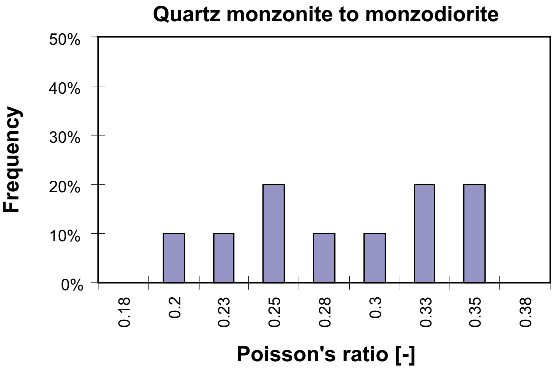


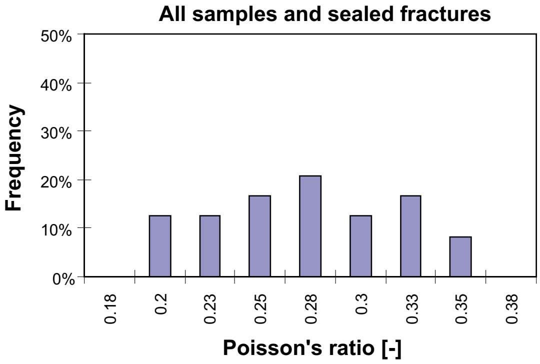


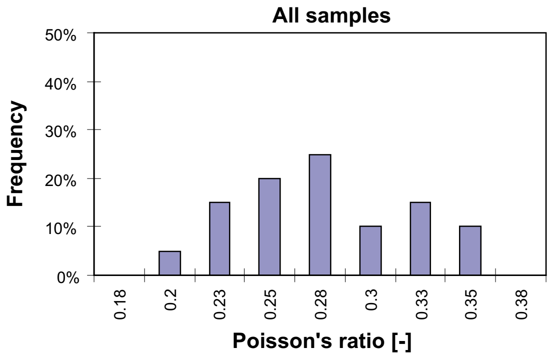
Poisson’s ratio from uniaxial tests



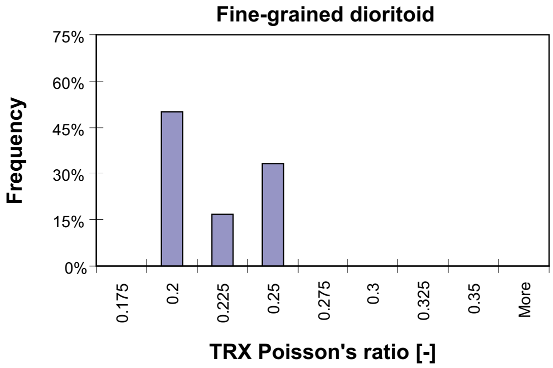


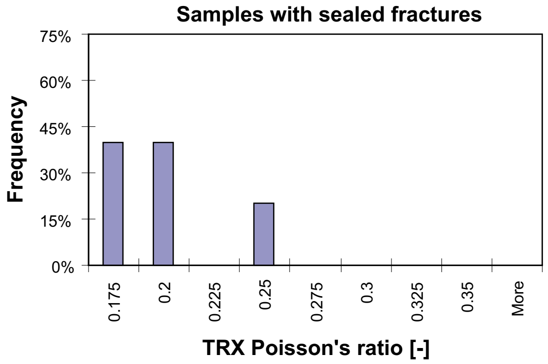


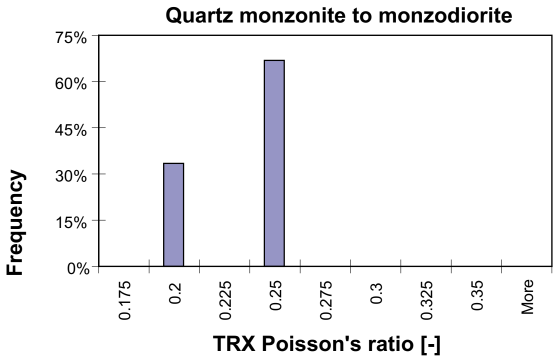


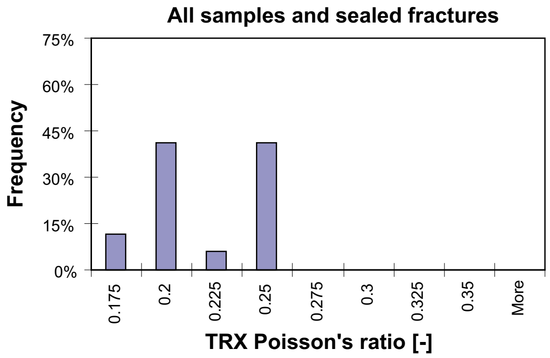


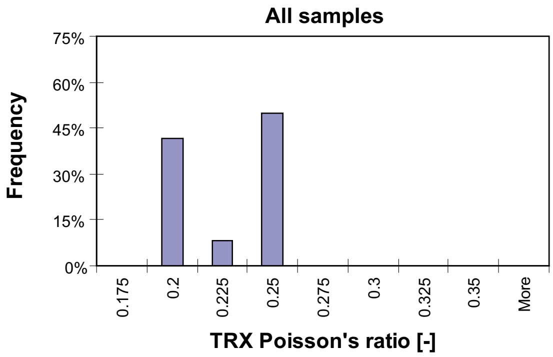
Poisson's ratio from triaxial tests







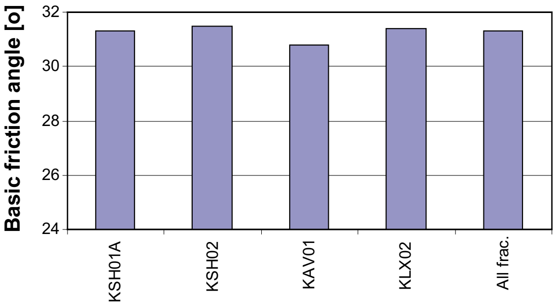


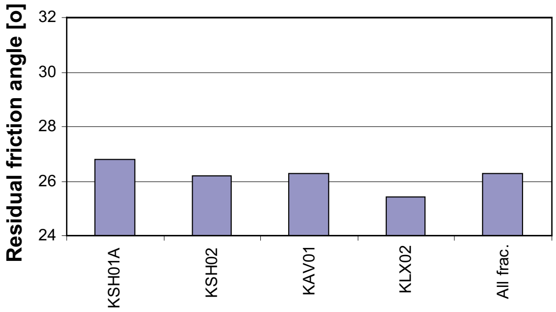


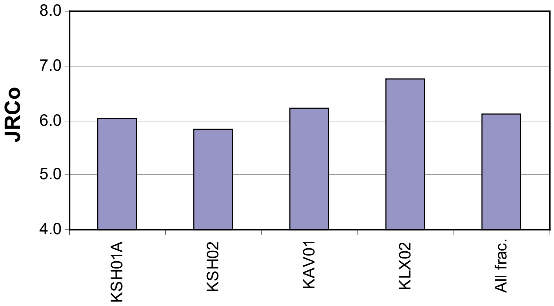
Appendix 2

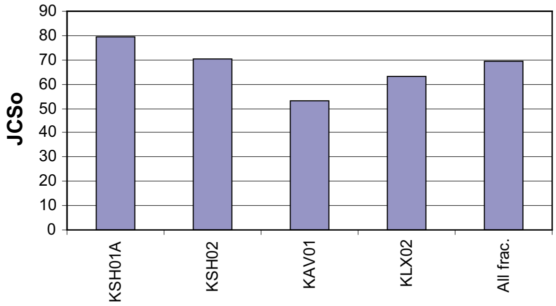
Rock fractures

Tilt tests – Barton-Bandis' parameters for each borehole

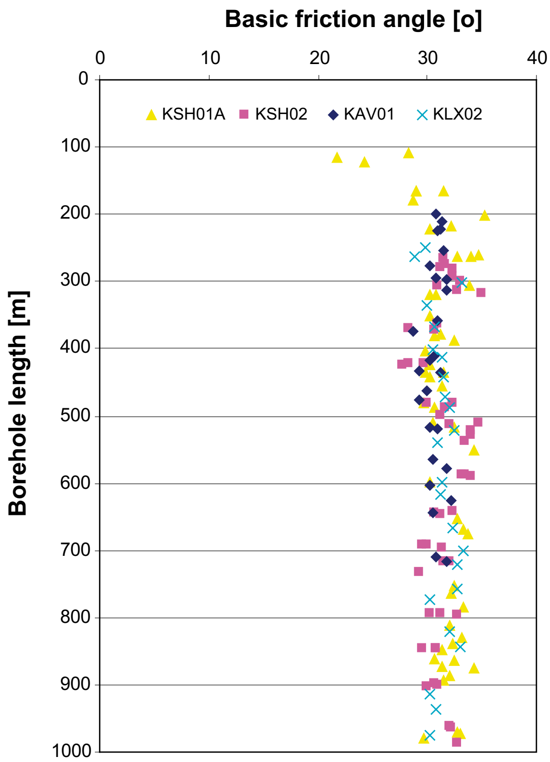


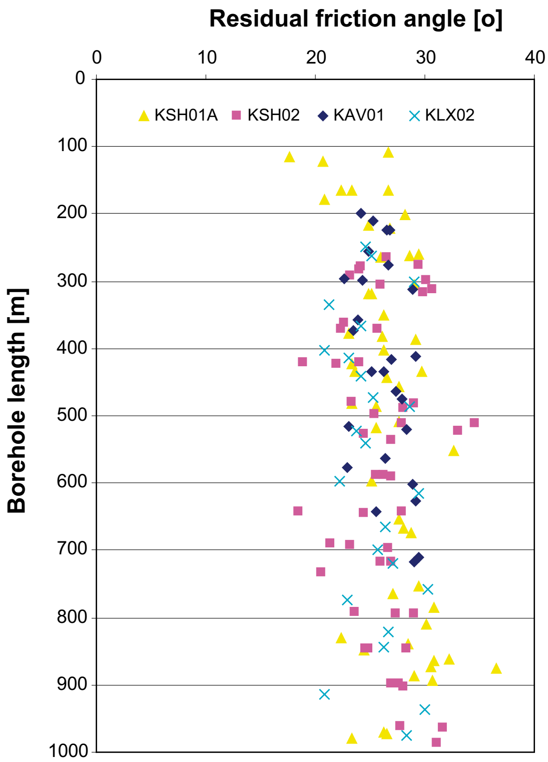


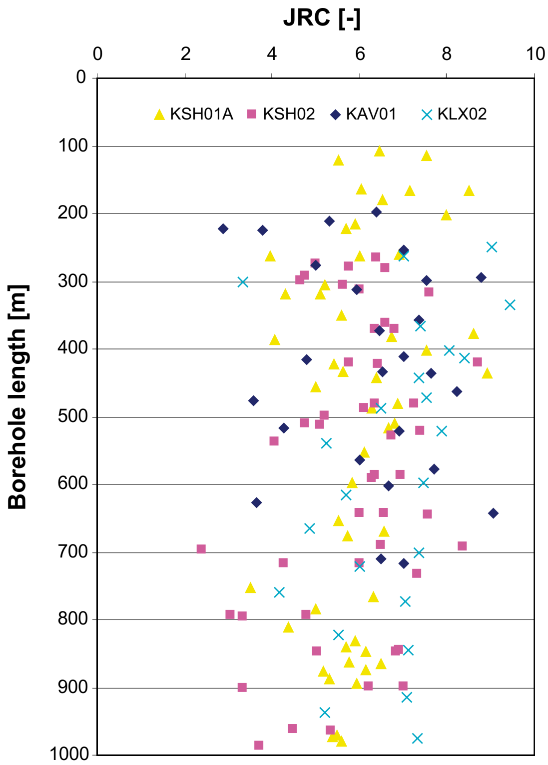


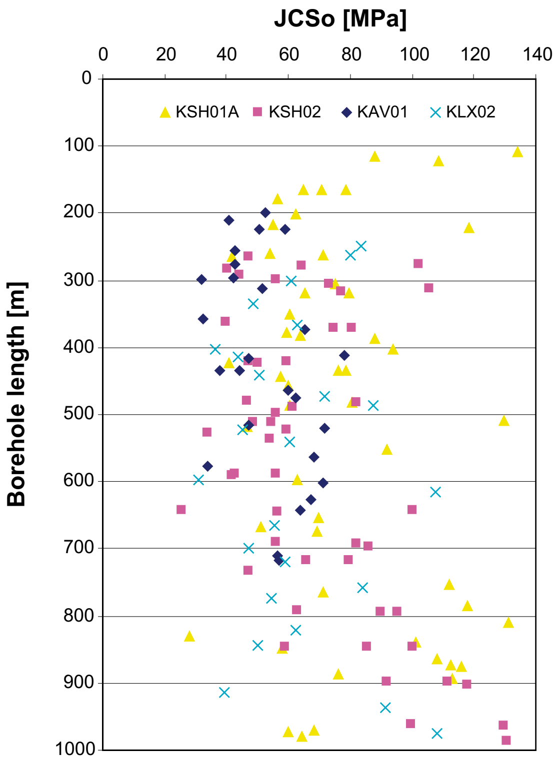


Tilt tests – Variation of the Barton-Bandis' parameters with borehole length







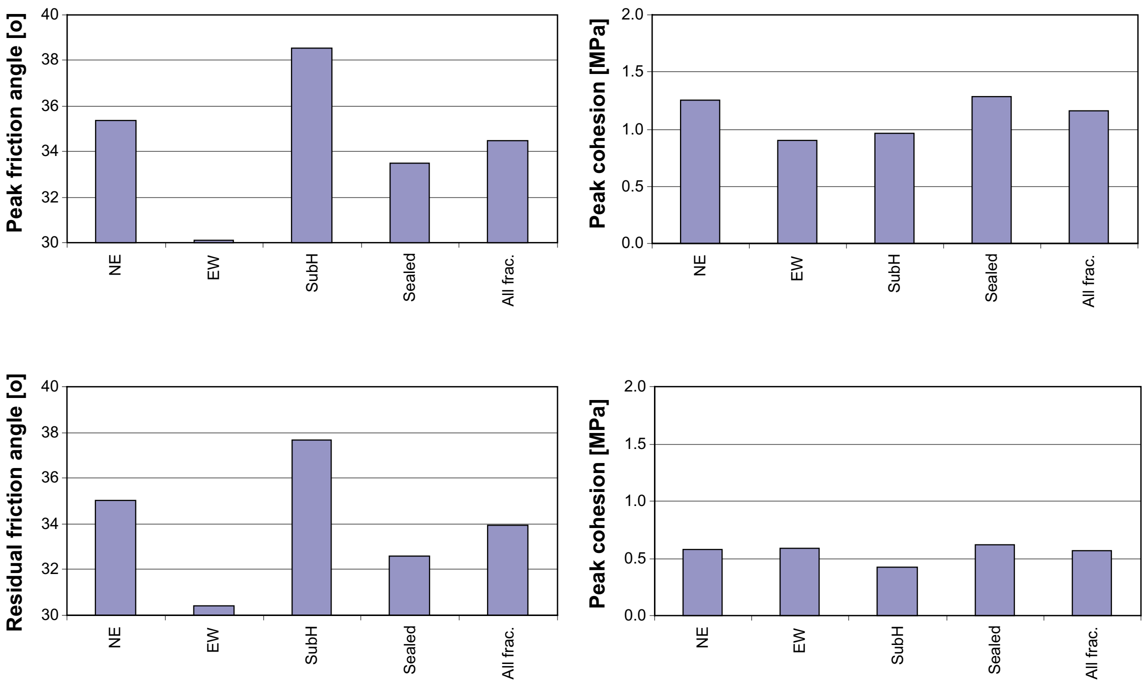


NGI Laboratory results – Coulomb's parameters from direct shear tests

Mechanical properties of fractures evaluated from laboratory tests (borehole KSH01A).

Test sample	Peak cohesion c' [MPa]	Peak friction angle φ' [°]	Residual cohesion [MPa]	Residual friction angle [°]
KSH01A-117-13	1.37	33	0.65	32
KSH01A-117-15	0.91	30	0.59	30
KSH01A-117-17	1.14	37	0.50	38
KSH01A-117-19	1.25	31	0.54	31
KSH01A-117-21	1.33	36	0.71	34
KSH01A-117-28	0.97	39	0.43	38

Average peak and residual friction angle and cohesion (borehole KSH01A).



SP Laboratory – Coulomb's parameters and stiffness from normal load and direct shear tests

Mechanical properties of fractures evaluated from laboratory tests (borehole KSH01A, KSH02A, KAV01).

Test sample	Peak cohesion c' [MPa]	Peak friction angle φ' [°]	Normal stiffness [MPa/mm]	Shear stiffness [MPa/mm]
KSH01A-117-1	0.687	26.6	154.5	20.2
KSH01A-117-2	1.138	27.6	75.7	35.6
KSH01A-117-3	0.503	32.9	84.8	36.4
KSH01A-117-4	0.194	32.4	113.3	34.4
KSH01A-117-5	0.479	36.0	130.7	17.0
KSH01A-117-8	0.585	29.9	114.6	39.7
KSH01A-117-9	0.218	30.4	179.3	29.1
KSH01A-117-10	0.392	35.9	864.0*	44.5
KSH01A-117-12	0.509	36.0	317.1*	37.7
KSH01A-117-14	0.065	36.7	87.1	40.1
KSH01A-117-16	0.193	35.5	146.3	23.3
KSH01A-117-18	0.545	29.4	85.7	27.6
KSH01A-117-20	0.182	35.4	57.7	21.5
KSH01A-117-22	0.825	27.0	83.6	33.2
KSH01A-117-25	0.881	24.4	135.6	29.0
KSH01A-117-26	1.657	23.8	130.3	25.3
KSH01A-117-27	0.58	34.7	69.9	16.5
KSH02A-117-1	0.19	32.1	49.2	10.3
KSH02A-117-2	1.035	29.1	80.9	42.3
KSH02A-117-4	0.091	40.7	109.4	40.0
KSH02A-117-5	0.483	27.5	101.1	38.4
KSH02A-117-6	0.343	33.3	113.4	10.6
KSH02A-117-7	0.273	33.9	101.9	30.9
KAV01-117-1	0.259	30.7	87.0	48.7
KAV01-117-2	0.392	34.8	57.9	19.3
KAV01-117-3	0.497	35.5	72.5	32.1
KAV01-117-4	0.309	34.2	102.3	20.9
KAV01-117-5	0.503	25.8	80.6	15.1

* For these tests, it was difficult to evaluate the normal stiffness. These values are neglected.