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Forsmark and Oskarshamn site investigation

Boreholes KFM01A and KSH01A

Inter-laboratory comparison of rock mechanics testing results

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Abstract

Laboratory testing of the mechanical and thermal properties of rock is a part of the activities performed during the current SKB site investigations. The laboratory testing is being conducted at SP, (the Swedish National Testing Institute) and at other laboratories. The objective of this investigation was to evaluate the comparative accuracy and precision of the test methods for indirect tensile strength, uni- and triaxial strength, shear strength, thermal expansion and heat capacity as conducted at the different laboratories. The core samples were obtained from borehole KFM01A at Forsmark and KSH01A at Oskarshamn.

A significant difference in the results from the different laboratories was detected for Poisson's ratio, peak shear stress and thermal expansion. However, no significant difference between the laboratories' results could be detected for thermal capacity, thermal diffusivity, thermal conductivity and compressive strength as determined in the uniaxial test. For Young's modulus, residual shear stress and indirect tensile strength the differences are questionable.

Investigations of causes for differences in the results are not part of the current commission. Although interviews with responsible personnel at the SP laboratories indicated that the reasons could be load application (interlayer) in the indirect tensile strength test, shear area and compensation for change of area during the shear test, stress level for calculation of the Poisson's ratio and conversion of readings for measuring thermal expansion.

Before any further investigation is performed, these differences between the laboratories must be examined further and eliminated. For future inter-laboratory comparisons of this nature, we recommend that the technically responsible at the laboratories go over the methods and the procedures (sample preparation, testing and data reduction) together, to identify and take care of the differences between the different laboratories. The thermal properties are measured by the same principle on equipment from the same supplier. It could therefore be of interest to compare the results with the results that are obtained by another measurement principle.

Sammanfattning

I SKB:s platsundersökningsprogram ingår laborationsprovning av bergmekaniska och termiska egenskaper /1/. Laborationsprovningarna beskrivs i SKB:s interna dokument, metodbeskrivningar, som utgör huvudreferenser för hur provningarna ska utföras och hur resultat ska redovisas /2/ – /7/. Huvuddelen av laboratorieprovningen görs av Sveriges Provnings- och Forskningsinstitut (SP). SKB har även kontrakterat ett antal så kallade sidolaboratorier för att göra jämförelseprovningar. I samband med provtagningen, för de bergmekaniska och termiska egenskaperna, i kärnborrhål KSH01A (AP PS 400-03-066) och KFM01A (AP PF 400-03-18) planerades och togs extra prover för jämförelseprovning. Syftet med jämförelseprovningen var dels att testa metodbeskrivningarnas tillämpbarhet på olika laboratorier och dels att verifiera huvudlaboratoriets resultat och utförande med hjälp av sidolaboratorium.

De bergmekaniska provningarna, /2/ – /5/, utgör så kallad förstörande provning och varje specifikt prov är unikt, dvs två exakt lika prover kan inte fås, vilket omöjliggör en direkt jämförelse av resultaten mellan två provningar. Detta medför att tolkning av delresultat från jämförelseprovningarna såsom provning/resultatkurvor, beteende under provningen och tendenser får betydelse och måste utnyttjas vid analysen av resultatjämförelsen. De termiska provningarna, /6/ – /7/, är inte förstörande och görs på samma prover varför resultaten från de olika laboratorierna kan jämföras direkt.

Spridningen i resultat inom laboratorierna kan ses som en indikation på metodernas repeterbarhet. I spridningen ingår dock materialspridning. Skillnaderna mellan laboratorierna indikerar metodernas reproducerbarhet, inklusive systematiska skillnader mellan laboratorierna. Någon signifikant skillnad kunde inte detekteras för värmekapacitet, termisk diffusivitet och konduktivitet samt tryckhållfasthet vid enaxligt tryckförsök. I några fall, E-modul, residual skjuvspänning och indirekt draghållfasthet, kan en mindre skillnad detekteras. För termisk längdutvidgning, Poissons tal och största skjuvspänning är skillnaden signifikant.

Denna typ av kvalitetsundersökning är ovanlig inom fältundersökningar och bergmekanisk provning trots att det, i båda fallen, kan vara avgörande med god precision vid provningen. Det är därför positivt att många resultat visar på god överensstämmelse, vilket tyder på att provtagning, provning och utvärdering genomförts på ett bra sätt.

Utredning av orsakerna till skillnaderna ingår inte i denna undersökning. Intervjuer med provningsansvariga tyder dock på att förfarandena vid provning inte är helt identiska. Detta kan förklara några av skillnaderna. Några exempel är lastens utbredning (mellanlägg) vid indirekt dragförsök, skjuvytans storlek och kompensation för förändrad skjuvyta vid normal- och skjuvförsök, lastområde vid beräkning av Poissons tal och omräkning av avläst värde vid mätning av längdförändring. För kommande undersökning rekommenderas att tekniskt ansvariga vid laboratorierna gemensamt går igenom metoderna och procedurerna vid de enskilda laboratorierna för att identifiera och eliminera eventuella skillnader. Mätning av de termiska egenskaperna har gjorts på likadan utrustning från samma leverantör. Det kan därför vara av intresse att jämföra resultaten med mätningar med en alternativ mätprincip för att värdera en eventuell bias i provningsutrustningen.

Contents

1 Introduction

Laboratory testing of rock mechanics properties and thermal properties is part of SKB's program for site investigation /1/. The laboratory testing had to be performed according to internally specified test methods /2/ – /7/. The Swedish National Testing Institute, SP, performed most of the testing. According to the programme, the laboratory test methods and the performance of the laboratories should be evaluated by inter-laboratory comparison of the testing results.

This document reports the results of the inter-laboratory comparison testing of drill cores from the Forsmark site, borehole KFM01A, and the Oskarshamn site, borehole KSH01A. The work was carried out in accordance with the activity plan AP PF 400-04-101 (SKB internal controlling document). The comparison testing was performed by HUT, University of Helsinki (mechanical properties), SINTEF (thermal expansion), Hot disc (thermal properties) and NGI, Norwegian Geotechnical Institute (normal stress and shear test on joints).

Samples for the inter-laboratory testing were selected in connection with the sampling for testing of mechanical and thermal properties of the drill cores from KFM01A (AP PF 400-03-18) and KSH01A (AP PS 400-03-066). The purpose of the study was to evaluate the comparative accuracy and precision of the test methods and the performance of the laboratories. The analyses were performed according to the appropriate parts of ISO 5725 /10/. The precision is normally expressed via repeatability and reproducibility.

The precision of a test method is according to ISO 5725 defined by the repeatability and the reproducibility. The repeatability gives a measure of the maximum difference that could be expected between two results if the same sample is tested at the same laboratory with the same equipment by the same operator at the same time. The repeatability is estimated by the in-laboratory standard deviation. The reproducibility provides a measure of the maximum difference that could be expected between two results if the same sample is tested by different laboratories and/or different equipment by different operators at different times. In general, the number of laboratories was too small to undertake a complete analysis of the accuracy and precision of the methods. The estimated difference between the laboratories should, therefore, be considered as indicative.

In some cases, the non-destructive testing, the same specimens could be used at different laboratories; in other cases, the destructive testing, this could not be done. The thermal properties and the thermal expansion were performed on the same samples at both laboratories. The samples were first tested at SP and then transported and tested at the alternative laboratory. The difference between the laboratories was estimated by means of the differences between test results of the laboratories. Testing of mechanical properties is all destructive testing. The comparisons were therefore performed on different samples. The specimens were sampled as near each other as possible and could therefore be considered as spot samples from the same batch.

2 Objective and scope

The purpose of the analysis was to evaluate the precision of the test methods and the performance of the different laboratories. The analyses were performed according to the relevant parts of ISO 5725. The following properties were compared.

Thermal expansion	Expansion between 20–40°C, 20–60°C and 20–80°C.
Thermal properties	Heat conductivity and heat capacity.
Uniaxial compressive strength test	Compressive strength, Young's modulus and Poisson's ratio at 50% of the peak value.
Triaxial compressive strength test	Compressive strength, Young's modulus and Poisson's ratio at different cell pressures: 2 MPa, 7 MPa and 10 MPa.
Indirect tensile strength	Maximum load, Indirect tensile strength.
Normal stress and shear tests on joints	Peak load stress, Residual load stress.

3 Testing Equipment

The equipment used in the specific tests is described in the reports on the tests. The calculations were performed using Microsoft Excel.

4 Execution

The analysis was performed according to the relevant parts of ISO 5725 /10/. The calculations were made according to ISO 3301 /8/ and ISO 2854 /9/in Microsoft Excel.

4.1 Description of the samples

The samples are described in the following tables. More information about the sampling, sample preparation and samples is given in the reports referred to in the tables.

Uniaxial compressive strength test

The samples were loaded in the axial direction to failure. The load and strain as well as the peak value of the axial stress were recorded. Furthermore, two elasticity parameters, Young's modulus and Poisson's ratio, were deduced from the tangent of the stress-strain curve at 50% of the peak load. The testing laboratories were the Swedish National Testing Institute (SP) and the University of Helsinki (HUT).

The tested samples are described in Table 4-1. Detailed information about the test is given in the P-reports P-04-176 /25/, P-04-182 /27/, P-04-207 /32/ and P-04-223 /34/.

Table 4-1. Samples for the uniaxial compressive strength test.

Sample identification	BH depth: start	BH depth: finish	Laboratory	Rock type	P-report/ result
KSH01A-113-1	299.27	299.42	SP	Quartz monzodiorite	P-04-207
KSH01A-113-2	300.40	300.55	HUT	Quartz monzodiorite	P-04-182
KSH01A-113-3	301.66	301.81	SP	Quartz monzodiorite	P-04-207
KSH01A-113-4	302.50	302.65	HUT	Quartz monzodiorite	P-04-182
KSH01A-113-5	303.04	303.19	SP	Quartz monzodiorite	P-04-207
KSH01A-113-6	309.88	310.03	HUT	Quartz monzodiorite	P-04-182
KSH01A-113-7	311.21	311.36	SP	Quartz monzodiorite	P-04-207
KSH01A-113-8	318.37	318.52	HUT	Quartz monzodiorite	P-04-182
KSH01A-113-9	319.59	319.74	SP	Quartz monzodiorite	P-04-207
KSH01A-113-10	319.59	319.74	HUT	Quartz monzodiorite	P-04-182
KFM01A-113-8	496.01	496.15	SP	Meta granodiorite-granite	P-04-223
KFM01A-113-9	496.15	496.30	HUT	Meta granodiorite-granite	P-04-176
KFM01A-113-10	496.45	496.59	SP	Meta granodiorite-granite	P-04-223
KFM01A-113-11	496.59	496.74	HUT	Meta granodiorite-granite	P-04-176
KFM01A-113-12	496.74	496.88	SP	Meta granodiorite-granite	P-04-223
KFM01A-113-13	495.46	495.61	HUT	Meta granodiorite-granite	P-04-176
KFM01A-113-14	497.14	497.28	SP	Meta granodiorite-granite	P-04-223
KFM01A-113-15	497.27	497.42	HUT	Meta granodiorite-granite	P-04-176
KFM01A-113-16	497.42	497.57	SP	Meta granodiorite-granite	P-04-223
KFM01A-113-17	497.56	497.71	HUT	Meta granodiorite-granite	P-04-176
KFM01A-113-18	497.76	497.90	SP	Meta granodiorite-granite	P-04-223
KFM01A-113-19	497.89	498.04	HUT	Meta granodiorite-granite	P-04-176

Triaxial compressive strength test

The samples were loaded in the axial direction to failure at different cell pressures. The load and strain as well as the peak value of the axial stress were recorded. Furthermore, two elasticity parameters, Young's modulus and Poisson's ratio, were estimated from the tangent of the stress-strain curve at 50% of the peak load. The testing laboratories were the Swedish National Testing Institute (SP) and the University of Helsinki (HUT). The tested samples are described in Table 4-2. Detailed information about the test is given in the P-reports P-04-177 /26/, P-04-183 /28/, P-04-208 /33/, and P-04-227 /35/.

Table 4-2. Samples for the triaxial compressive strength test.

Sample identification	BH depth: start	BH depth: finish	Laboratory	Rock type	Cell pressure	P-report/ result
KSH01A-115-1	298.81	298.86	SP	Quartz monzodiorite	2	P-04-208
KSH01A-115-2	305.16	305.31	HUT	Quartz monzodiorite	2	P-04-183
KSH01A-115-3	306.23	306.38	SP	Quartz monzodiorite	7	P-04-208
KSH01A-115-4	308.84	309.00	HUT	Quartz monzodiorite	7	P-04-183
KSH01A-115-5	312.86	313.01	SP	Quartz monzodiorite	2	P-04-208
KSH01A-115-6	312.85	313.01	HUT	Quartz monzodiorite	2	P-04-183
KSH01A-115-7	321.00	321.15	SP	Quartz monzodiorite	7	P-04-208
KSH01A-115-8	321.00	321.15	HUT	Quartz monzodiorite	7	P-04-183
KSH01A-115-9	321.58	321.73	SP	Quartz monzodiorite	10	P-04-208
KSH01A-115-10	323.34	323.49	HUT	Quartz monzodiorite	10	P-04-183
KFM01A-115-5	498.42	498.56	SP	Meta granodiorite-ranite	2	P-04-227
KFM 01A-115-6	501.17	501.32	HUT	Meta granodiorite-granite	2	P-04-177
KFM01A-115-7	498.70	498.84	SP	Meta granodiorite-granite	7	P-04-227
KFM 01A-115-8	498.84	498.99	HUT	Meta granodiorite-granite	7	P-04-177
KFM01A-115-9	498.99	499.13	SP	Meta granodiorite-granite	2	P-04-227
KFM 01A-115-10	499.13	499.28	HUT	Meta granodiorite-granite	2	P-04-177
KFM01A-115-11	499.42	499.57	SP	Meta granodiorite-granite	7	P-04-227
KFM 01A-115-12	499.56	499.71	HUT	Meta granodiorite-granite	7	P-04-177
KFM01A-115-13	499.71	499.86	SP	Meta granodiorite-granite	10	P-04-227
KFM 01A-115-14	495.14	495.29	HUT	Meta granodiorite-granite	10	P-04-177

Indirect tensile strength test

The testing, using the Brazilian test, was carried out in a load frame equipped with a pair of curved bearing blocks. The samples were tested to breakage and the maximum load was recorded. The testing laboratories were the Swedish National Testing Institute (SP) and the University of Helsinki (HUT). The tested samples are described in Table 4-3. Detailed information about the test is given in the P-reports P-04-62 /18/, P-04-170 /22/, P-04-171 /23/ and P-04-184 /29/.

Table 4-3. Samples for the indirect (Brazilian) tensile strength test.

Sample identification	BH depth: start	BH depth: finish	Laboratory	Rock type	P-report/ result
KSH01A-110-1	302.80	302.85	SP	Quartz monzodiorite	P-04-62
KSH01A-110-2	303.46	303.51	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-3	303.51	303.56	SP	Quartz monzodiorite	P-04-62
KSH01A-110-4	305.26	305.31	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-5	306.01	306.06	SP	Quartz monzodiorite	P-04-62
KSH01A-110-6	306.38	306.43	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-7	310.18	310.23	SP	Quartz monzodiorite	P-04-62
KSH01A-110-8	310.52	310.57	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-9	310.57	310.62	SP	Quartz monzodiorite	P-04-62
KSH01A-110-10	310.62	310.67	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-11	313.22	313.27	SP	Quartz monzodiorite	P-04-62
KSH01A-110-12	313.27	313.32	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-13	318.67	318.72	SP	Quartz monzodiorite	P-04-62
KSH01A-110-14	318.72	318.71	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-15	319.16	319.20	SP	Quartz monzodiorite	P-04-62
KSH01A-110-16	319.20	319.25	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-17	319.25	319.30	SP	Quartz monzodiorite	P-04-62
KSH01A-110-18	320.04	320.09	HUT	Quartz monzodiorite	P-04-184
KSH01A-110-19	320.09	320.13	SP	Quartz monzodiorite	P-04-62
KSH01A-110-20	321.73	321.78	HUT	Quartz monzodiorite	P-04-184
KFM01A-110-14	491.50	491.54	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-15	491.54	491.58	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-16	492.50	492.54	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-17	492.54	492.58	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-18	492.99	493.04	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-19	493.04	493.08	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-20	494.73	494.77	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-21	494.77	494.81	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-22	496.30	496.34	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-23	496.34	496.38	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-24	496.38	496.42	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-25	497.02	497.06	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-26	498.04	498.08	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-27	498.08	498.12	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-28	498.12	498.16	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-29	498.23	498.27	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-30	498.27	498.31	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-31	498.31	498.35	HUT	Meta granodiorite-granite	P-04-171
KFM01A-110-32	497.71	497.76	SP	Meta granodiorite-granite	P-04-170
KFM01A-110-33	494.43	494.47	HUT	Meta granodiorite-granite	P-04-171

The normal stress and shear tests on joints

The test was performed in two steps: the samples were first subject to normal loading (two cycles) and then shearing until the peak shear stress was reached, followed by a residual shear stress being clearly defined. The test was repeated three times at three different normal stresses. The testing laboratories were the Swedish National Testing Institute (SP) and the Norwegian Geotechnical Institute (NGI). The tested samples are described in Table 4-4. Detailed information about the test is given in the P-reports P-04-175 /24/ and P-04-185 /30/, P-05-06 /15/ and P-05-08 /36/.

Table 4-4. Samples for testing normal stress and shear tests on joints.

Sample identification	BH depth: start	BH depth: finish	Laboratory	Rock type	P-report/ result
KSH01A-117-12	479.37	479.51	SP		P-05-06
KSH01A-117-13	483.54	483.68	NGI	Fine-grained diorite	P-04-185
KSH01A-117-14	485.65	485.76	SP		P-05-06
KSH01A-117-15	485.93	486.05	NGI	Fine-grained diorite	P-04-185
KSH01A-117-16	488.37	488.46	SP		P-05-06
KSH01A-117-17	488.87	489.01	NGI	Fine-grained diorite	P-04-185
KSH01A-117-18	490.32	490.45	SP		P-05-06
KSH01A-117-19	492.83	493.04	NGI	Fine-grained diorite	P-04-185
KSH01A-117-20	494.06	494.18	SP		P-05-06
KSH01A-117-21	495.27	495.38	NGI	Fine-grained diorite	P-04-185
KSH01A-117-22	495.45	495.55	SP		P-05-06
KSH01A-117-23	497.87	497.96	NGI	Fine-grained diorite	P-04-185
KSH01A-117-28	709.52	709.70	NGI	Quartz monozodiorite	P-04-185
KFM01A-117-5	229.34	229.44	SP		P-05-08
KFM01A-117-6	229.44	229.51	NGI	Fine-grained granodiorite	P-04-175
KFM01A-117-4	230.11	230.21	NGI	Fine-grained granodiorite	P-04-175
KFM01A-117-3	233.55	233.67	SP		P-05-08
KFM01A-117-7	234.36	234.43	SP		P-05-08
KFM01A-117-8	234.43	234.50	NGI	Fine-grained granodiorite	P-04-175
KFM01A-117-1	235.58	235.67	SP		P-05-08
KFM01A-117-2	235.67	235.76	NGI	Fine-grained granodiorite	P-04-175
KFM01A-117-9	390.10	390.23	SP		P-05-08
KFM01A-117-10	390.23	390.33	NGI	Fine-grained granodiorite	P-04-175
KFM01A-117-11	390.39	390.50	SP		P-05-08
KFM01A-117-12	699.67	699.79	SP		P-05-08

Thermal conductivity, thermal diffusivity and specific heat capacity

The principle of the TPS method is to place a circular temperature probe and heater between two pieces of the sample. This probe consists of an Ni-spiral covered by an insulating material (MICA or KAPTON). During the measurement, constant power is emitted by the sensor and the heating of the specimen is recorded simultaneously. The data are then reduced in the Hot Disk software and the thermal conductivity (TC), thermal diffusivity (TD) and specific heat capacity (Cp) are determined.

Each sample was tested at two laboratories. The tested samples are described in Table 4-5. The testing laboratories were the Swedish National Testing Institute (SP) and Hot Disk AB (HD). Detailed information about the test is given in the P-reports P-04-53 /16/, P-04-159 /19/, P-04-160 /20/ and P-04-186 /31/.

Table 4-5. Samples for testing the thermal conductivity (TC), thermal diffusivity (TD) and specific heat capacity (Cp).

Sample identification	BH depth: start	BH depth: finish	Laboratory	Testing temperature	P-report
KSH01A-90V-1	299.15	299.27	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-2	300.21	300.33	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-3	300.33	300.45	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-4	301.94	302.06	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-5	305.89	306.01	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-7	399.27	399.39	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-9	401.63	401.75	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-10	404.00	404.12	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KSH01A-90V-11	404.12	404.24	SP, HD	+ 20, 50, 80°C	P-04-53, P-04-160
KFM01A-90V-11	492.39	492.51	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-12	493.74	493.85	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-13	493.85	493.97	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-14	493.97	494.09	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-15	494.09	494.20	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-16	494.20	494.32	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-17	494.32	494.43	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-18	494.51	494.62	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-19	494.62	494.74	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186
KFM01A-90V-20	494.82	494.94	SP, HD	+ 20, 50, 80°C	P-04-159, P-04-186

Coefficient of thermal expansion

Determination of the coefficient of thermal expansion was made according to SKB's method description SKB MD 191.002-version 1.9 (SKB internal controlling document). The test is non-destructive. The comparison test was therefore performed on the same samples at both laboratories for the intervals 20–40°C, 20–60°C and 20–80°C.

Each sample was tested at two laboratories. The testing laboratories were the Swedish National Testing Institute (SP) and SINTEF. The tested samples are described in Tables 4-6 and 4-7. Detailed information about the test and the results from the test at SP is given in the P-report P-04-59 /17/ and P-04-163 /21/. Detailed information about the test and the results from the test at SP are given in the P-report P-05-59 /13/ and P-05-60 /14/.

Table 4-6. Samples from KSH01A for testing the coefficient of thermal expansion.

Sample identification	BH depth: start	BH depth: finish	Laboratory	P-report/results
KSH01A-90L-1	297.59	297.86	SP,SINTEF	P-04-59, P-05-59
KSH01A-90L-2	297.86	298.13	SP, SINTEF	P-04-59, P-05-59
KSH01A-90L-3	300.75	301.02	SP, SINTEF	P-04-59, P-05-59
KSH01A-90L-4	301.39	301.66	SP, SINTEF	P-04-59, P-05-59
KSH01A-90L-7	399.00	399.27	SP, SINTEF	P-04-59, P-05-59
KSH01A-90L-8	400.10	400.37	SP, SINTEF	P-04-59, P-05-59
KSH01A-90L-9	400.37	400.64	SP, SINTEF	P-04-59, P-05-59
KSH01A-90L-10	400.64	400.91	SP, SINTEF	P-04-59, P-05-59
KSH01A-90L-11	401.21	401.48	SP, SINTEF	P-04-59, P-05-59

Table 4-7. Samples from KFM01A for testing the coefficient of thermal expansion.

Sample identification	BH depth: start	BH depth: finish	Laboratory	P-report/results
KFM01A-90L-7	490.46	490.72	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-8	490.72	490.98	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-9	490.98	491.25	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-10	491.25	491.51	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-11	491.58	491.84	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-12	491.84	492.12	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-13	492.12	492.38	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-14	492.60	492.85	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-15	493.20	493.47	SP, SINTEF	P-04-163, P-05-60
KFM01A-90L-16	493.47	493.73	SP, SINTEF	P-04-163, P-05-60

4.2 Testing

The precision of the test methods is described by the repeatability and reproducibility of the method. The repeatability describes the closeness of agreement between independent test results obtained under repeatability conditions, i.e. testing with the same method of identical test items in the same laboratory with the same equipment by the same operator within a short interval of time. The reproducibility describes the closeness of agreement between independent test results obtained under reproducibility conditions, i.e. testing with the same method of identical test items in different laboratories with different operators using different equipment. The precision of test methods is normally estimated according to ISO 5725, Accuracy (trueness and precision) of test methods and results. It is common to choose 8 to 15 laboratories to achieve a proper estimate of the precision. This investigation was in principle performed according to ISO 5725 with the following deviations.

- Only two laboratories participated for each method. The estimates describe the variation inside the laboratories and between the two laboratories.
- The samples were from two boreholes. It was not possible to guarantee that the samples were identical. The variation, repeatability and reproducibility thus contain contributions from the variation in the individual samples.
- In two cases, thermal expansion and thermal diffusivity, the tests were performed on the same samples and could therefore be considered as identical test items. Storing in water could, however, to a lesser extent, change the properties of the samples.

The determinations of coefficient of thermal expansion, thermal conductivity, thermal diffusivity and specific heat capacity were performed on the same samples at both laboratories. The difference between the methods could therefore be evaluated according to ISO 3301, Statistical interpretation of data – Comparison of two means in the case of paired observations. In the other cases, the variation was calculated according to ISO 2854. All calculations were performed in Microsoft Excel.

5 Results

5.1 Uniaxial compressive strength test

The results from the laboratories are shown in Table 5-1. The entire series of results of the tests can be found in the reports listed in Table 5-1. The results from the comparison are presented in Table 5-2. In Figures 5-1 to 5-3 the 95% confidence intervals of the results from HUT are plotted against the corresponding results from SP.

Table 5-1. Results from the uniaxial compressive strength tests, SP and HUT.

Sample identification	Laboratory	Compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio	P-report/ result
KFM01A-113-9	HUT	234.3	75.0	0.29	P-04-176
KFM01A-113-11	HUT	247.3	75.9	0.29	P-04-176
KFM01A-113-13	HUT	239.2	74.2	0.29	P-04-176
KFM01A-113-15	HUT	236.9	75.8	0.30	P-04-176
KFM01A-113-17	HUT	237.0	75.0	0.28	P-04-176
KFM01A-113-19	HUT	237.7	75.2	0.30	P-04-176
KFM01A-113-8	SP	187.4	78.9	0.24	P-04-223
KFM01A-113-10	SP	229.3	76.1	0.20	P-04-223
KFM01A-113-12	SP	261.6	76.5	0.22	P-04-223
KFM01A-113-14	SP	238.9	74.2	0.18	P-04-223
KFM01A-113-16	SP	235.6	75.3	0.23	P-04-223
KFM01A-113-18	SP	288.6	78.0	0.18	P-04-223
KSH01A-113-2	HUT	169.5	69.0	0.34	P-04-182
KSH01A-113-4	HUT	147.5	55.8	0.33	P-04-182
KSH01A-113-6	HUT	179.1	69.6	0.33	P-04-182
KSH01A-113-8	HUT	169.1	80.5	0.30	P-04-182
KSH01A-113-10	HUT	186.4	73.4	0.32	P-04-182
KSH01A-113-1	SP	158.3	68.7	0.31	P-04-207
KSH01A-113-3	SP	167.7	66.0	0.33	P-04-207
KSH01A-113-5	SP	170.4	66.7	0.27	P-04-207
KSH01A-113-7	SP	192.9	82.9	0.32	P-04-207
KSH01A-113-9	SP	186.0	78.6	0.33	P-04-207

Table 5-2. Comparison of results from the uniaxial compressive strength tests.

Borehole	Laboratory	Number of samples	Mean value	Standard deviation	95% confidence interval max	Min
Compressive strength (MPa)						
KFM01A	HUT	6	238.7	4.5	244.5	232.9
KFM01A	SP	6	240.3	33.9	284.0	196.5
KSH01A	HUT	5	170.3	14.7	193.2	147.4
KSH01A	SP	5	175.0	14.1	197.1	153.0
Young's modulus (GPa)						
KFM01A	HUT	6	75.2	0.6	76.0	74.4
KFM01A	SP	6	76.5	1.7	78.7	74.3
KSH01A	HUT	5	69.7	9.0	83.7	55.6
KSH01A	SP	5	72.6	7.7	84.6	60.6
Poisson's Ratio						
KFM01A	HUT	6	0.292	0.008	0.301	0.282
KFM01A	SP	6	0.209	0.024	0.240	0.177
KSH01A	HUT	5	0.324	0.015	0.348	0.300
KSH01A	SP	5	0.312	0.023	0.348	0.277

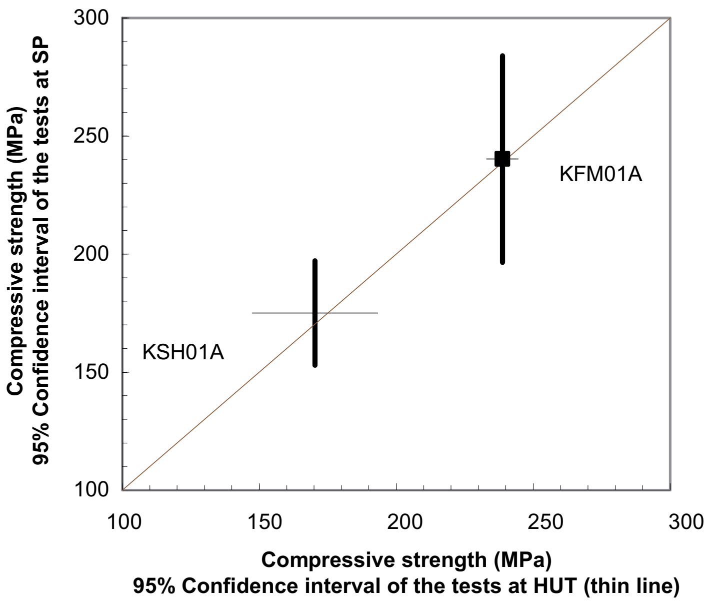

Figure 5-1. *Diagram showing the results of the uniaxial compressive strength tests. The length of the horizontal and vertical lines indicates the length of the confidence interval of the measured compressive strength at HUT and SP, respectively. The point where the lines cross displays the mean values of the laboratories. The diagonal line illustrates where the cross should be if the results were the same.*

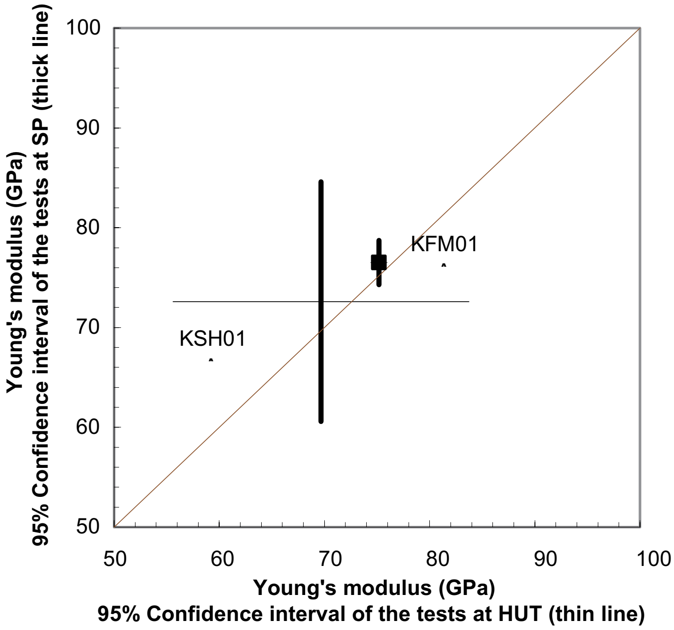

Figure 5-2. *Diagram showing the measurement of Young's modulus in the uniaxial compressive strength test. The length of the horizontal and vertical lines describes the length of the confidence interval of the Young's modulus values from HUT and SP, respectively. The point where the lines cross displays the mean values of the laboratories. The diagonal line illustrates where the cross should be if the results were the same.*

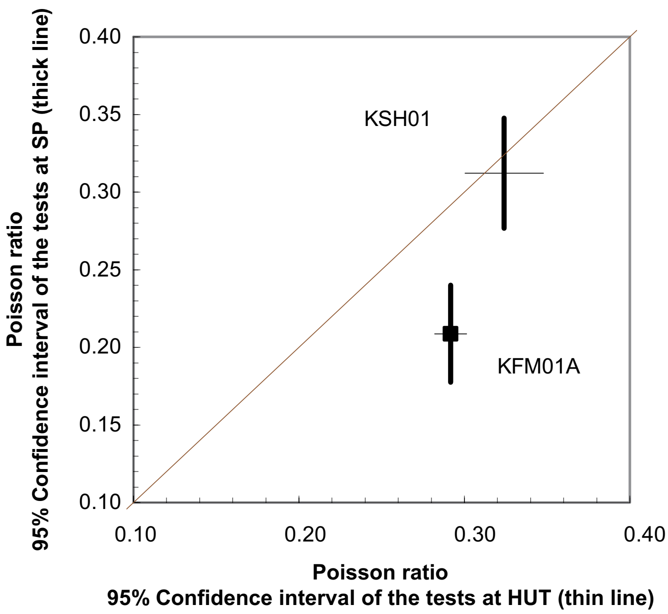

Figure 5-3. *Diagram showing the measurement of Poisson's ratio at the uniaxial compressive strength test. The length of the horizontal and vertical lines describes the length of the confidence interval of the Poisson's ratio at HUT and SP, respectively. The point where the lines cross displays the mean values from the laboratories. The diagonal line illustrates where the cross should be if the results were the same.*

Regarding compressive strength and Young's modulus, no significant difference can be seen between the laboratories, although the confidence interval for the KFM01A core samples was much longer for the SP lab than that for HUT. These results are most encouraging. However, the measured Poisson's ratio of the samples from KFM01A tested at SP is about 30% lower than the corresponding results from HUT. This result indicates a systematic difference between the laboratories.

5.2 Triaxial compressive strength test

The results from the triaxial strength tests are shown in Table 5-3, whereas the comparison between SP and HUT is presented in Table 5-4. Maximum two samples were tested at each cell pressure. Maximum and minimum values (and hence the range) of the results were therefore used as the comparison parameter.

In Figures 5-4 to 5-6 the range from HUT is plotted against the result from SP.

Table 5-3. Results from the triaxial compressive strength tests SP and HUT.

Sample identification	Laboratory	Compressive strength (MPa)	Young's modulus (GPa)	Poisson's Ratio	Confining pressure (MPa)	P-report/ result
KFM01A-115-6	HUT	247.4	75.3	0.31	2	P-04-176
KFM01A-115-8	HUT	262.8	76.3	0.29	7	P-04-176
KFM01A-115-10	HUT	353.4	78.3	0.28	2	P-04-176
KFM01A-115-12	HUT	348.2	76.2	0.29	7	P-04-176
KFM01A-113-14	HUT	384.7	79.6	0.29	10	P-04-176
KSH01A-115-2	HUT	206.9	78.6	0.29	2	P-04-183
KSH01A-115-4	HUT	167.2	74.7	0.29	7	P-04-183
KSH01A-115-6	HUT	202.8	68.7	0.28	2	P-04-183
KSH01A-115-8	HUT	260.1	83.0	0.34	7	P-04-183
KSH01A-115-10	HUT	223.9	83.1	0.31	10	P-04-183
KFM01A-115-5	SP	311.0	75.1	0.23	2	P-04-227
KFM01A-115-7	SP	282.2	75.1	0.19	7	P-04-227
KFM01A-115-9	SP	379.5	74.2	0.18	2	P-04-227
KFM01A-115-11	SP	376.1	75.0	0.23	7	P-04-227
KFM01A-115-13	SP	371.3	74.1	0.25	10	P-04-227
KSH01A-115-1	SP	181.6	67.8	0.23	2	P-04-208
KSH01A-115-3	SP	194.2	67.6	0.24	7	P-04-208
KSH01A-115-5	SP	245.8	89.1	0.22	2	P-04-208
KSH01A-115-7	SP	250.8	75.8	0.22	7	P-04-208
KSH01A-115-9	SP	289.6	79.0	0.17	10	P-04-208

Table 5-4. Comparison of results from triaxial compressive strength tests: mean, standard deviation and confidence interval.

Drill hole	Laboratory	Number of samples	Confining pressure (Mpa)	Mean value	Min. value	Max. value
Compressive strength (MPa)						
KFM01A	HUT	2	2	255.1	247.4	262.8
	HUT	2	7	350.8	348.2	353.4
	HUT	1	10	384.7		
KFM01A	SP	2	2	296.6	282.2	311.0
	SP	2	7	377.8	376.1	379.5
	SP	1	10	371.3		
KSH01A	HUT	2	2	187.1	167.2	206.9
	HUT	2	7	231.5	202.8	260.1
	HUT	1	10	223.9		
KSH01A	SP	2	2	187.9	181.6	194.2
	SP	2	7	248.3	245.8	250.8
	SP	1	10	289.6		
Young's modulus (GPa)						
KFM01A	HUT	2	2	75.8	75.3	76.3
	HUT	2	7	77.3	76.2	78.3
	HUT	1	10	79.6		
KFM01A	SP	2	2	75.1	75.1	75.1
	SP	2	7	74.6	74.2	75.0
	SP	1	10	74.1		
KSH01A	HUT	2	2	76.7	74.7	78.6
	HUT	2	7	75.9	68.7	83.0
	HUT	1	10	83.1		
KSH01A	SP	2	2	67.7	67.6	67.8
	SP	2	7	82.4	75.8	89.1
	SP	1	10	79.0		
Poisson's Ratio						
KFM01A	HUT	2	2	0.30	0.29	0.31
	HUT	2	7	0.29	0.28	0.29
	HUT	1	10	0.29		
KFM01A	SP	2	2	0.21	0.19	0.23
	SP	2	7	0.20	0.18	0.23
	SP	1	10	0.25		
KSH01A	HUT	2	2	0.29	0.29	0.29
	HUT	2	7	0.31	0.28	0.34
	HUT	1	10	0.31		
KSH01A	SP	2	2	0.23	0.23	0.24
	SP	2	7	0.22	0.22	0.22
	SP	1	10	0.17		

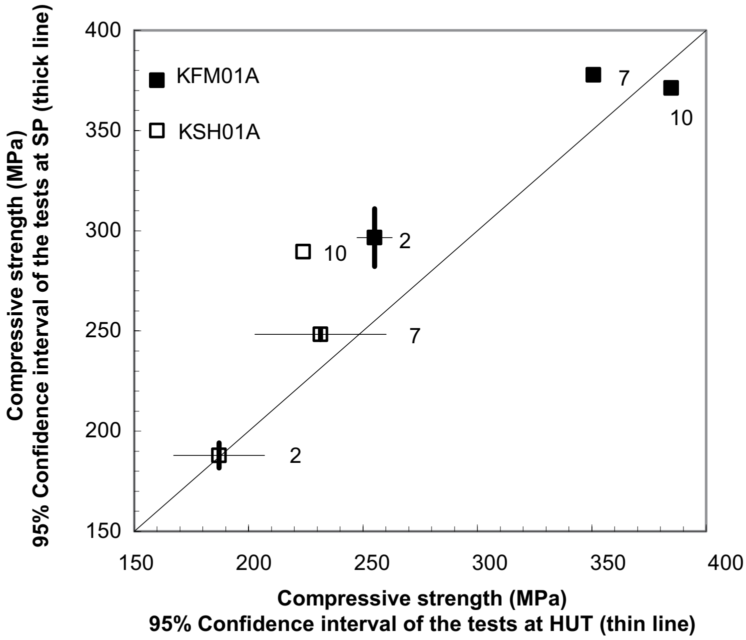

Figure 5-4. Diagram illustrating the measurement of compressive strength from the triaxial compressive strength test. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured compressive strength at HUT and SP, respectively. The point where the lines cross shows the mean values of the laboratories. The figures to the right of the points indicate the confining pressure. The diagonal line displays where the cross should be if the results from the laboratories were the same.

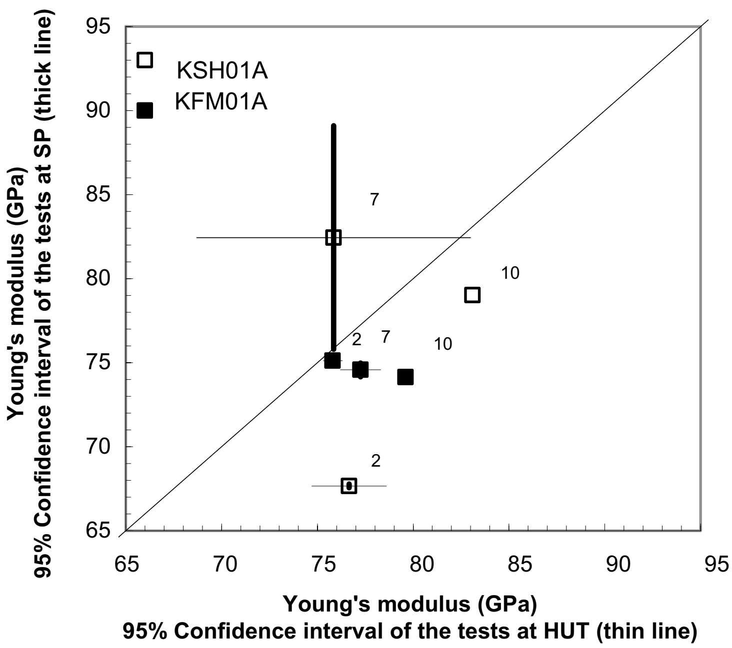

Figure 5-5. Diagram illustrating the measurement of Young's modulus from the triaxial compressive strength test. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured compressive strength at HUT and SP, respectively. The point where the lines cross shows the mean values of the laboratories. The figures to the right of the points indicate the confining pressure. The diagonal line displays where the cross should be if the results from the laboratories were the same.

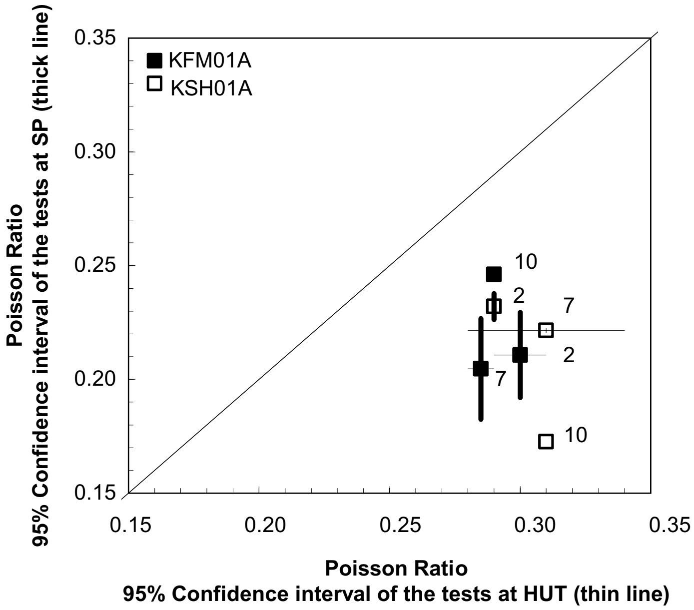

Figure 5-6. *Diagram showing the measurement of Poisson ratio in the triaxial compressive strength test. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured Poissons ratio at HUT and SP, respectively. The point where the lines cross displays the mean values of the laboratories. The figures to the right of the points indicate the confining pressure. The diagonal line illustrates where the cross should be if the results from the laboratories were the same.*

The number of samples is too few for a complete statistical analysis. The results indicate that the results regarding compressive strength from SP are somewhat higher than the results from HUT. The measured Poisson's ratio of KFM01A at SP is about 30% lower than at HUT, see also the results from the uniaxial compressive test, Figure 5-3.

5.3 Indirect tensile strength test

Results from indirect tensile strength tests are presented in Table 5-5, and the comparison between the two test laboratories SP and HUT is given in Table 5-6.

Table 5-5. Results from indirect tensile strength tests SP and HUT.

Sample identification	Laboratory	Maximum peak load (KN)	Tensile strength (MPa)	P-report/ result
KFM01A-110-14	SP	27.6	13.5	P-04-170
KFM01A-110-15	HUT	30.7	15.0	P-04-171
KFM01A-110-16	SP	25.3	12.3	P-04-170
KFM01A-110-17	HUT	30.9	15.1	P-04-171
KFM01A-110-18	SP	28.8	14.1	P-04-170
KFM01A-110-19	HUT	31.6	15.5	P-04-171
KFM01A-110-20	SP	28.3	13.7	P-04-170
KFM01A-110-21	HUT	30.8	15.2	P-04-171
KFM01A-110-22	SP	29.3	14.4	P-04-170
KFM01A-110-23	HUT	28.8	14.1	P-04-171
KFM01A-110-24	SP	25.6	12.5	P-04-170
KFM01A-110-25	HUT	33.7	16.2	P-04-171
KFM01A-110-26	SP	28.2	13.6	P-04-170
KFM01A-110-27	HUT	30.8	15.0	P-04-171
KFM01A-110-28	SP	28.3	13.7	P-04-170
KFM01A-110-29	HUT	31.7	15.4	P-04-171
KFM01A-110-30	SP	27.6	13.5	P-04-170
KFM01A-110-31	HUT	31.0	15.0	P-04-171
KFM01A-110-32	SP	30.9	14.9	P-04-170
KFM01A-110-33	HUT	33.0	16.2	P-04-171
KSH01A-110-1	SP	24.7	12.0	P-04-62
KSH01A-110-10	HUT	31.3	15.1	P-04-184
KSH01A-110-11	SP	35.6	17.6	P-04-62
KSH01A-110-12	HUT	29.4	14.3	P-04-184
KSH01A-110-13	SP	32.9	15.9	P-04-62
KSH01A-110-14	HUT	33.5	16.2	P-04-184
KSH01A-110-15	SP	31.3	15.2	P-04-62
KSH01A-110-16	HUT	30.9	14.9	P-04-184
KSH01A-110-17	SP	32.8	15.9	P-04-62
KSH01A-110-18	HUT	28.0	13.5	P-04-184
KSH01A-110-19	SP	32.7	15.9	P-04-62
KSH01A-110-2	HUT	32.2	15.6	P-04-184
KSH01A-110-20	HUT	33.7	16.4	P-04-184
KSH01A-110-3	SP	24.9	12.4	P-04-62
KSH01A-110-4	HUT	32.4	15.6	P-04-184
KSH01A-110-5	SP	31.2	15.1	P-04-62
KSH01A-110-6	HUT	33.6	16.2	P-04-184
KSH01A-110-7	SP	30.8	15.0	P-04-62
KSH01A-110-8	HUT	33.6	16.3	P-04-184
KSH01A-110-9	SP	32.9	15.9	P-04-62

Table 5-6. Comparison of results from indirect tensile strength tests: mean, standard deviation and confidence interval.

Borehole	Laboratory	Number of samples	Mean value	Standard deviation	95% confidence interval max	Min
Maximum load (kN)						
KFM01A	HUT	10	31.3	1.3	30.2	32.4
KFM01A	SP	10	28.2	1.7	26.7	29.9
KSH01A	HUT	10	31.9	2.0	30.2	33.5
KSH01A	SP	10	31.0	3.5	28.0	34.5
Indirect tensile strength (MPa)						
KFM01A	HUT	10	15.3	0.6	14.7	15.9
KFM01A	SP	10	13.7	0.8	12.9	14.5
KSH01A	HUT	10	15.4	1.0	14.4	16.4
KSH01A	SP	10	15.1	1.7	13.4	16.8

The difference between the laboratories is small. However, for the samples from KFM01A, a small but significant difference can be seen.

5.4 The normal stress and shear tests on joints

Results from normal and shear tests on joints performed by SP and NGI are displayes in Table 5-7. Comparison of results between the two laboratories is shown in Table 5-8.

The measurement range from HUT is plotted versus the results from SP in Figure 5-7, whereas in Figures 5-8 to 5-11 the results from NGI are plotted against results from SP.

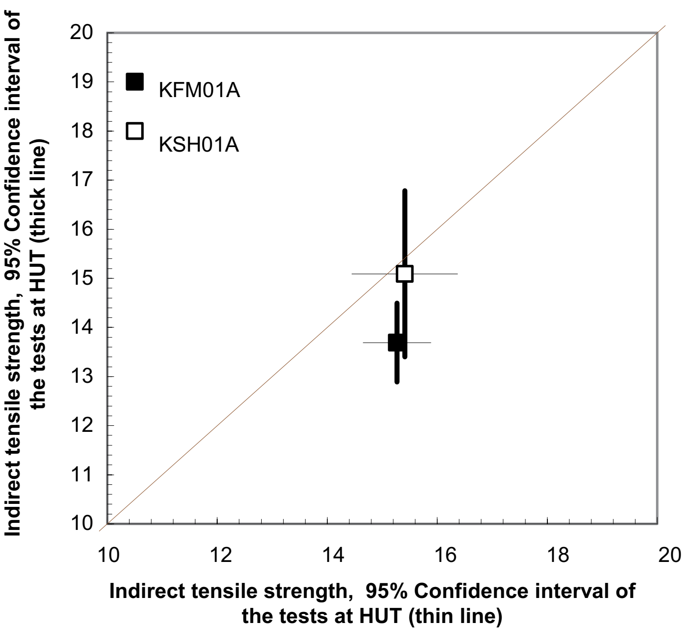

Figure 5-7. Diagram showing the measurement of the indirect tensile strength. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured indirect tensile strength at HUT and SP, respectively. The point where the lines cross indicates the mean values of the laboratories. The diagonal line shows where the cross should be if the results from the laboratories were the same.

Table 5-7. Results from the normal and shear tests SP and NGI.

Sample identification	Laboratory	Fracture Area (cm²)	Normal stress at 0.5 MPa (MPa)		Normal stress at 5 Mpa (MPa)		Normal stress at 20 Mpa (MPa)		P-report/ result
			Peak shear stress	Res. shear stress	Peak shear stress	Res. shear stress	Peak shear stress	Res. shear stress	
KFM01A-117-2	NGI	24.7	1.40	0.8	4.38	3.09	16.22	13.9	P-04-175
KFM01A-117-4	NGI	24.2	1.72	0.89	4.68	3.5	18.04	11.6	P-04-175
KFM01A-117-6	NGI	24.3	2.11	0.84	4.92	4.76	15.12	14.7	P-04-175
KFM01A-117-8	NGI	24.4	1.57	0.88	4.87	3.36	16.28	13.65	P-04-175
KFM01A-117-10	NGI	23.2	1.51	1.1	5.43	4.59	16.29	12	P-04-175
KFM01A-117-1	SP	35.3	0.63	0.58	3.29	3.25	13.26	12.76	P-05-08
KFM01A-117-3	SP	30.5	0.73	0.57	4.07	3.70	15.84	14.68	P-05-08
KFM01A-117-5	SP	47.5	0.98	0.54	3.76	3.38	13.91	13.59	P-05-08
KFM01A-117-7	SP	33.1	1.20	0.62	4.34	4.23	13.63	8.25	P-05-08
KFM01A-117-9	SP								
KFM01A-117-11	SP	33.0	0.44	0.39	3.50	3.39	14.66	12.06	P-05-08
KFM01A-117-12	SP	46.8	0.50	0.46	3.88	3.38	13.31	10.06	P-05-08
KSH01A-117-13	NGI	24.80	1.87	0.85	4.43	3.95	14.64	13.25	P-04-185
KSH01A-117-15	NGI	23.10	1.16	0.78	3.82	3.65	12.50	12.30	P-04-185
KSH01A-117-17	NGI	22.90	1.43	0.93	5.10	4.30	16.33	15.92	P-04-185
KSH01A-117-19	NGI	24.70	1.70	0.87	4.02	3.50	13.14	12.57	P-04-185
KSH01A-117-21	NGI	22.90	1.96	0.97	4.58	4.20	16.11	14.25	P-04-185
KSH01A-117-23	NGI	21.90	1.38	0.75	5.06	4.95	17.87	15.35	P-04-185
KSH01A-117-28	NGI	24.25	1.43	0.89	4.91	4.19	16.85	15.90	P-04-185
KSH01A-117-12	SP	52.1	0.75	0.57	4.30	3.77	15.05	11.91	P-05-05
KSH01A-117-14	SP	25.8	0.51	0.47	3.69	3.48	14.97	14.11	P-05-05
KSH01A-117-16	SP	32.7	0.64	0.44	3.64	3.58	14.48	14.36	P-05-05
KSH01A-117-18	SP	28.6	0.99	0.39	3.15	3.05	11.86	11.41	P-05-05
KSH01A-117-20	SP	26.6	0.63	0.51	3.62	3.01	14.44	14.35	P-05-05
KSH01A-117-22	SP	23.5	0.81	0.61	3.72	2.97	10.92	10.38	P-05-05

Table 5-8. Comparison of results from the normal and shear tests: mean, standard deviation and confidence interval.

Drill hole	Normal stress	Laboratory	Mean value (MPa)	Standard deviation (MPa)	95% confidence interval Lower level (MPa)	Upper level (MPa)
Peak shear stress						
KFM01A	0.5	NGI	1.66	0.28	1.23	2.09
		SP	0.75	0.29	0.37	1.12
	5	NGI	4.86	0.38	4.25	5.46
		SP	3.81	0.38	3.32	4.30
	20	NGI	16.39	1.05	14.75	18.03
		SP	14.10	0.99	12.82	15.38

Drill hole	Normal stress	Laboratory	Mean value (MPa)	Standard deviation (MPa)	95% confidence interval Lower level (MPa)	Upper level (MPa)
KSH01	0.5	NGI	1.56	0.29	1.24	1.89
		SP	0.66	0.21	0.42	0.91
	5	NGI	4.56	0.50	4.00	5.12
		SP	3.24	1.23	1.86	4.62
	20	NGI	15.35	1.99	13.12	17.58
		SP	11.99	4.60	6.83	17.15
Residual shear stress						
KFM01A	0.5	NGI	0.90	0.12	0.72	1.08
		SP	0.53	0.09	0.42	0.64
	5	NGI	3.86	0.76	2.67	5.05
		SP	3.56	3.56	3.09	4.02
	20	NGI	13.17	1.32	11.11	15.23
		SP	11.90	11.90	8.84	14.96
KSH01	0.5	NGI	0.86	0.08	0.78	0.95
		SP	0.44	0.17	0.25	0.63
	5	NGI	4.11	0.48	3.57	4.64
		SP	2.91	1.09	1.69	4.14
	20	NGI	14.22	1.55	12.49	15.95
		SP	11.18	4.46	6.18	16.18

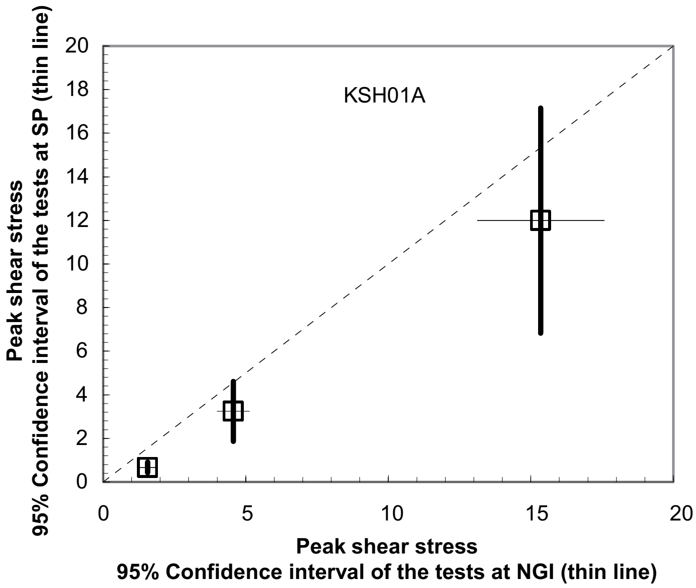

Figure 5-8. *Diagram with the measurement results of peak shear stress of the samples from KSH01A. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured peak shear stress at NGI and SP, respectively. The point where the lines cross shows the mean values of the laboratories. The diagonal line illustrates where the cross should be if the results from the laboratories were the same.*

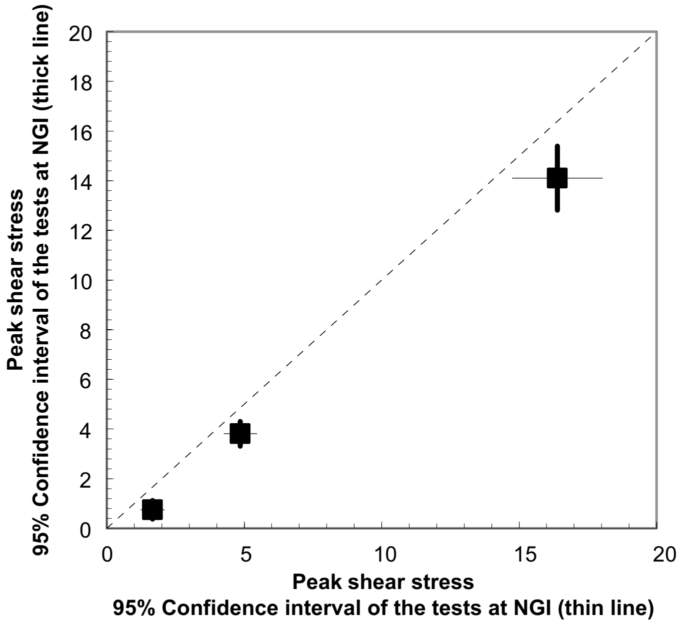

Figure 5-9. *Diagram illustrating the measurements of peak shear stress of the samples from KFM01A. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured peak shear stress at NGI and SP, respectively. The point where the lines cross shows the mean values of the laboratories. The diagonal line displays where the cross should be if the results from the laboratories were the same.*

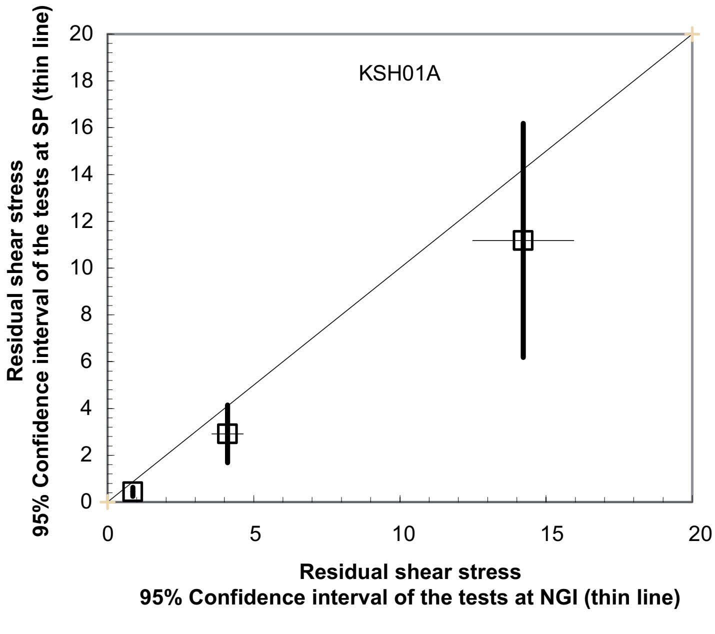

Figure 5-10. *Diagram showing the measurements of residual shear stress. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured residual shear stress at NGI and SP, respectively. The point where the lines cross shows the mean values of the laboratories. The diagonal line illustrates where the cross should be if the results from the laboratories were the same.*

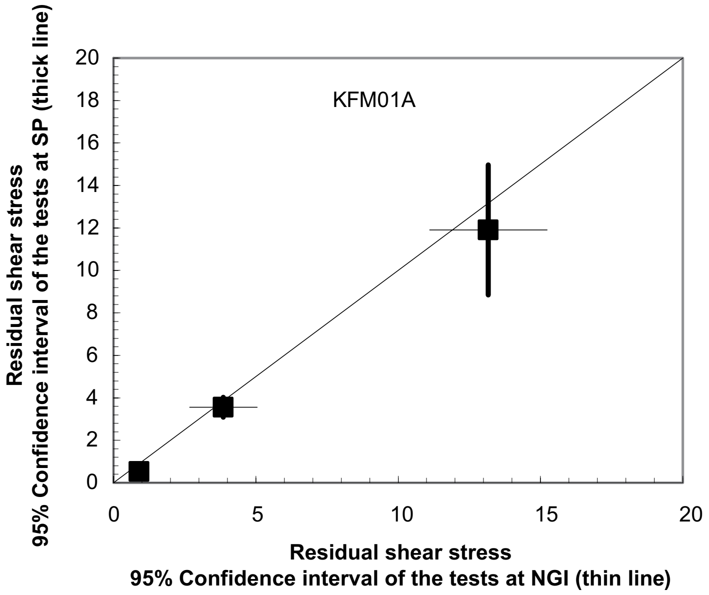

Figure 5-11. *Diagram with the measurements of residual shear stress. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured residual shear stress at NGI and SP, respectively. The point where the lines cross illustrates the mean values of the laboratories. The diagonal line shows where the cross should be if the results from the laboratories were the same.*

The number of samples is too few for a complete statistic analysis. However, the results are quite similar and hence encouraging. It is clear, however, that the measured peak shear stress at SP is about 20% lower than the measured value at NGI. Regarding residual shear stress, the difference is smaller.

5.5 Coefficient of thermal expansion

The entire series of results from testing of KSH01A at SP and SINTEF can be found in P-04-59 and P-05-59 respectively. All results from the testing of KFM01A at SP and SINTEF are presented in P-04-163 and P-05-60 respectively. The results from the evaluation of the test measurements are given in Tables 5-9 and 5-10 and in Figures 5-12 to 5-14.

Table 5-9. Results from testing the thermal expansion at SP and SINTEF on paired samples from KFM01A.

Sample identification	Thermal expansion, 20 to 80°C, (mm/mm*°C)*10^{-6}			Thermal expansion, 20 to 60°C, (mm/mm*°C)*10^{-6}			Thermal expansion, 20 to 40°C, (mm/mm*°C)*10^{-6}		
	SINTEF	SP	Difference	SINTEF	SP	Difference	SINTEF	SP	Difference
KFM01A-90L-7	41.0	8.67	32.3	48.3	7.74	40.6	42.6	6.75	35.9
KFM01A-90L-8	16.7	5.49	11.2	21.3	6.75	14.6	25.1	5.96	19.1
KFM01A-90L-9	36.4	7.54	28.8	41.4	8.14	33.3	33.9	7.15	26.7
KFM01A-90L-10				9.40	6.15	3.25	31.3	6.35	25.0
KFM01A-90L-11	16.7	3.57	13.1	24.4	4.76	19.7	30.1	5.56	24.5
KFM01A-90L-12	4.60	6.22	1.62	5.02	5.26	0.24	20.1	5.96	14.1
KFM01A-90L-13	15.9	8.93	6.95	18.8	7.44	11.4	23.8	7.34	16.5
KFM01A-90L-14	46.8	8.01	38.8	49.5	6.65	42.8	41.4	5.76	35.6
KFM01A-90L-15	28.4	6.88	21.6	29.5	6.75	22.7	31.4	6.75	24.6
KFM01A-90L-16	28.4	6.68	21.7	37.6	5.96	31.7	37.6	6.75	30.9
Mean value	26.1	6.89	19.2	28.5	6.56	22.0	31.7	6.43	25.3
Standard deviation	13.7	1.68	13.0	15.5	1.06	15.0	7.43	0.61	74.1
Upper 95% confidence level	38.7	8.43	7.33	41.7	7.46	9.25	38.0	6.95	19.0
Lower 95% confidence level	13.5	5.35	31.1	15.4	5.66	34.7	25.4	5.92	31.6

Table 5-10. Results from testing the thermal expansion at SP and SINTEF on paired samples from KSH01A.

Sample identification	Thermal expansion, 20 to 80°C, (mm/mm*°C)*10^{-6}			Thermal expansion, 20 to 60°C, (mm/mm*°C)*10^{-6}			Thermal expansion, 20 to 40°C, (mm/mm*°C)*10^{-6}		
	SINTEF	SP	Difference	SINTEF	SP	Difference	SINTEF	SP	Difference
KSH01A-90L-1	28.95	5.76	23.19	24.64	2.98	21.66	34.24	4.76	29.47
KSH01A-90L-2	17.40	6.75	10.65	25.16	7.05	18.11	34.66	7.54	27.12
KSH01A-90L-3	25.24	7.74	17.50	29.75	8.04	21.71	30.79	6.55	24.23
KSH01A-90L-4	19.43	9.33	10.10	24.78	9.53	15.25	32.06	6.15	25.91
KSH01A-90L-7	29.92	5.76	24.17	30.48	4.07	26.41	38.41	5.76	32.66
KSH01A-90L-8	30.01	0.00	30.01	31.54	5.26	26.28	36.76	6.15	30.61
KSH01A-90L-9	33.00	5.16	27.83	36.34	5.16	31.18	41.35	7.74	33.61
KSH01A-90L-10	32.06	7.01	25.05	32.41	6.85	25.56	38.48	6.75	31.73
KSH01A-90L-11	25.87	4.83	21.04	30.04	4.86	25.18	36.30	5.76	30.54
Mean value	26.88	6.54	20.33	29.46	5.98	23.48	35.89	6.35	29.54
Standard deviation	5.44	1.49	3.95	3.96	2.06	1.90	3.33	0.93	2.40
Upper 95% confidence level	31.86	8.04	23.83	33.09	7.86	25.23	38.95	7.20	31.75
Lower 95% confidence level	21.89	5.05	16.84	25.83	4.09	21.74	32.84	5.50	27.34

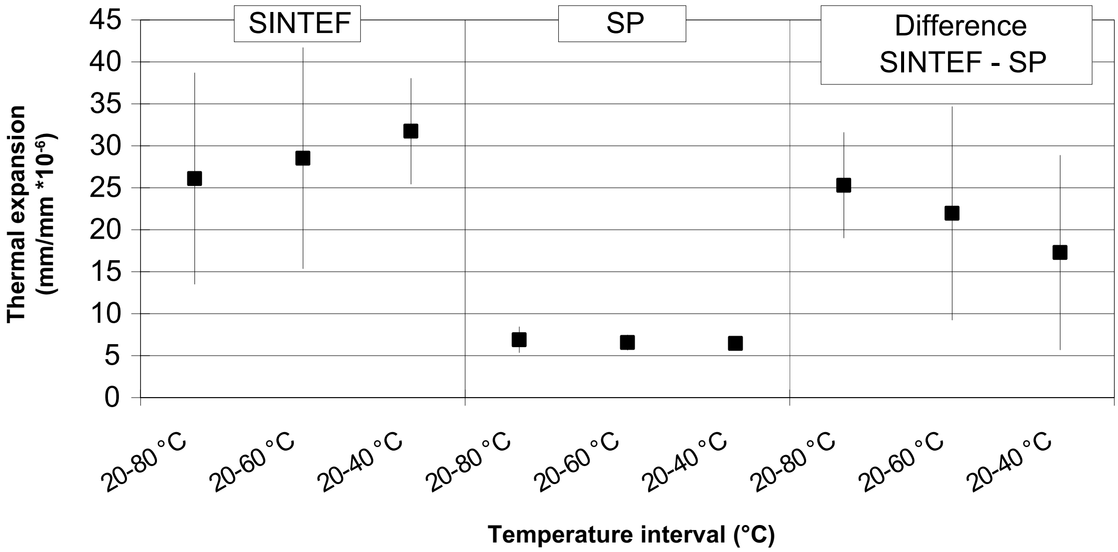

Figure 5-12. *Diagram showing the results of the measurement of thermal expansion of samples from KFM01A at the two laboratories. The diagram displays the mean value and 95% confidence interval of the results and the mean value and confidence interval of the difference between the laboratories.*

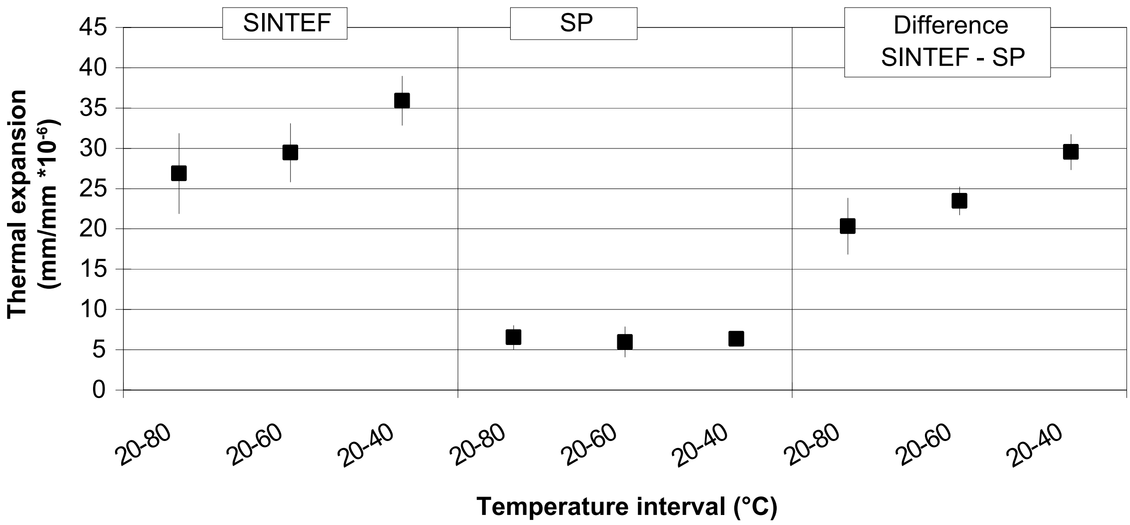

Figure 5-13. *Diagram illustrating the results of the measurements of thermal expansion of samples from KSH01A at the two laboratories. The diagram shows the mean value and 95% confidence interval of the results and the mean value and confidence interval of the difference between the laboratories.*

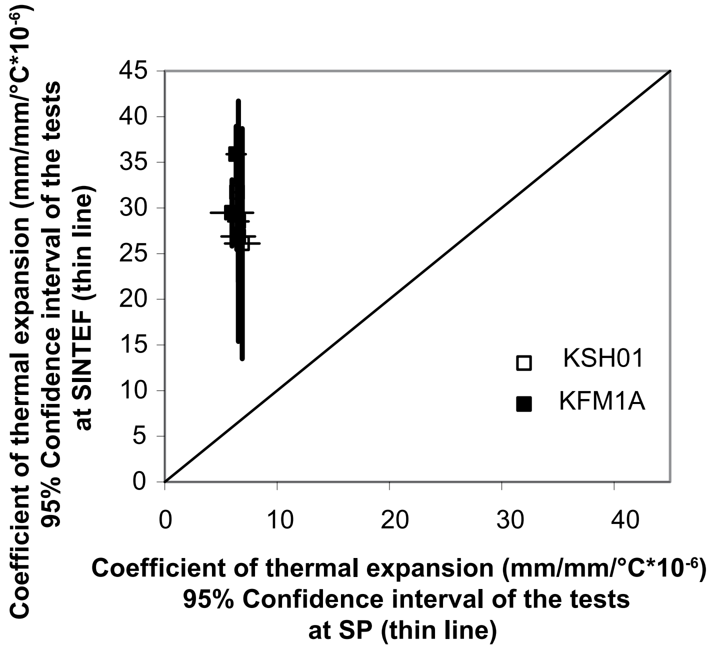

Figure 5-14. *Diagram illustrating the measurements of thermal expansion. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured thermal expansion at SINTEF and SP, respectively. The point where the lines cross shows the mean values of the laboratories. The diagonal line indicates where the cross should be if the results from the laboratories were the same.*

Figures 5-12, 5-13 and 5-14 show the mean value and 95% confidence interval of the measured thermal expansion of the samples and also the paired differences between the laboratories. The results from SINTEF are about four times higher than the results from SP. The standard deviation (confidence interval) of the mean is also higher. One reason for this difference could be that the measured value at SINTEF has not been multiplied by the scale factor of the instrument, this factor being 3.97 at SP.

5.6 Thermal properties

The entire series of results from testing of KSH01A and KFM01A at SP and HD can be found in P-04-53, P-04-186, P-04-159 and P-04-160. The results from the evaluation of the test measurements are given in Tables 5-11 to 5-16 and Figures 5-15 to 5-20.

Table 5-11. Results from testing the thermal properties at 20°C at SP and Hot Disk (HD) on paired samples from KSH01A.

Identification	Test temperature (°C)	Thermal Conductivity (W/m/K)			Thermal Diffusivity (mm²/s)			Heat Capacity (MJ/m³/K)		
		HD	SP	HD-SP	HD	SP	HD-SP	HD	SP	HD-SP
KSH01A-90V-1	20	2.81	2.74	–0.07	1.26	1.22	–0.04	2.23	2.24	0.01
KSH01A-90V-2	20	2.88	2.80	–0.08	1.24	1.21	–0.03	2.33	2.31	–0.02
KSH01A-90V-3	20	2.85	2.80	–0.05	1.29	1.23	–0.06	2.22	2.28	0.06
KSH01A-90V-4	20	2.94	2.79	–0.15	1.27	1.25	–0.02	2.31	2.23	–0.08
KSH01A-90V-5	20	2.88	2.78	–0.10	1.28	1.31	0.03	2.26	2.13	–0.13
KSH01A-90V-7	20	2.75	2.75	0.00	1.24	1.20	–0.04	2.23	2.29	0.06
KSH01A-90V-9	20	3.09	3.02	–0.07	1.32	1.29	–0.03	2.33	2.35	0.02
KSH01A-90V-10	20	2.94	2.87	–0.07	1.35	1.36	0.01	2.17	2.11	–0.06
KSH01A-90V-11	20	2.86	2.80	–0.06	1.89*	1.17		2.41	2.39	–0.02
Mean value		2.89	2.82	–0.07	1.28	1.25	–0.02	2.28	2.26	–0.02
Standard deviation		0.10	0.09	0.04	0.04	0.06	0.03	0.07	0.09	0.06
Upper 95% confidence level		2.98	2.90	–0.04	1.32	1.30	0.01	2.34	2.34	0.04
Lower 95% confidence level		2.80	2.74	–0.11	1.24	1.19	–0.05	2.21	2.17	–0.08

Table 5-12. Results from testing the thermal properties at 20°C at SP and Hot Disk (HD) on paired samples from KFM01A.

Identification	Test temperature (°C)	Thermal Conductivity (W/m/K)			Thermal Diffusivity (mm²/s)			Heat Capacity (MJ/m³/K)		
		HD	SP	HD-SP	HD	SP	HD-SP	HD	SP	HD-SP
KFM01A-90V-11	20	3.85	3.80	–0.05	1.67	1.66	–0.01	2.32	2.30	–0.02
KFM01A-90V-12	20	3.84	3.67	–0.17	1.65	1.59	–0.06	2.33	2.31	–0.02
KFM01A-90V-13	20	3.71	3.54	–0.17	1.70	1.69	–0.01	2.18	2.09	–0.09
KFM01A-90V-14	20	3.83	3.89	0.06	1.69	1.60	–0.09	2.27	2.43	0.16
KFM01A-90V-15	20	3.82	3.89	0.07	1.66	1.64	–0.02	2.30	2.37	0.07
KFM01A-90V-16	20	3.78	3.68	–0.10	1.90	1.88	-0.02	1.99	1.96	–0.03
KFM01A-90V-17	20	3.76	3.75	–0.01	1.78	1.61	–0.17	2.12	2.33	0.21
KFM01A-90V-18	20	3.64	3.67	0.03	1.85	1.79	–0.05	1.97	2.05	0.08
KFM01A-90V-19	20	3.72	3.72	0.00	1.74	1.68	–0.06	2.14	2.21	0.07
KFM01A-90V-20	20	3.98	4.00	0.02	1.77	1.72	–0.04	2.25	2.32	0.07
Mean value		3.79	3.76	–0.03	1.74	1.69	–0.05	2.19	2.24	0.05
Standard deviation		0.09	0.14	0.09	0.08	0.09	0.05	0.13	0.15	0.09
Upper 95% confidence level		3.87	3.88	0.04	1.81	1.76	–0.01	2.30	2.37	0.13
Lower 95% confidence level		3.71	3.65	–0.11	1.67	1.61	–0.09	2.08	2.11	–0.03

Table 5-13. Results from testing the thermal properties at 50°C at SP and Hot Disk (HD) on paired samples from KSH01A.

Identification	Test temperature (°C)	Thermal Conductivity (W/m/K)			Thermal Diffusivity (mm^2/s)			Heat Capacity ($MJ/m^3/K$)		
		HD	SP	HD-SP	HD	SP	HD-SP	HD	SP	HD-SP
KSH01A-90V-1	50	2.82	2.76	–0.06	1.13	1.13	0.00	2.49	2.45	–0.04
KSH01A-90V-2	50	2.89	2.81	–0.08	1.20	1.11	–0.09	2.41	2.53	0.12
KSH01A-90V-3	50	2.81	2.77	–0.04	1.18	1.14	–0.04	2.39	2.43	0.04
KSH01A-90V-4	50	2.89	2.80	–0.09	1.14	1.16	0.02	2.54	2.41	–0.13
KSH01A-90V-5	50	2.85	2.78	–0.07	1.08	1.22	0.14	2.64	2.27	–0.37
KSH01A-90V-7	50	2.76	2.73	–0.03	1.17	1.12	–0.05	2.35	2.44	0.09
KSH01A-90V-9	50	3.04	2.99	–0.05	1.22	1.19	–0.03	2.50	2.51	0.01
KSH01A-90V-10	50	2.88	2.82	–0.06	1.22	1.22	0.00	2.36	2.31	–0.05
KSH01A-90V-11	50	2.81	2.77	–0.04	1.11	1.09	–0.02	2.50	2.55	0.05
Mean value		2.86	2.80	–0.06	1.16	1.15	–0.01	2.46	2.43	–0.03
Standard deviation		0.08	0.08	0.02	0.05	0.05	0.07	0.10	0.09	0.15
Upper 95% confidence level		2.93	2.87	–0.04	1.21	1.20	0.05	2.55	2.52	0.10
Lower 95% confidence level		2.79	2.73	–0.08	1.12	1.11	–0.07	2.38	2.35	–0.17

Table 5-14. Results from testing the thermal properties at 50°C at SP and Hot Disk (HD) on paired samples from KFM01A.

Sample identification	Test temperature (°C)	Thermal Conductivity (W/m/K)			Thermal Diffusivity (mm^2/s)			Heat Capacity ($MJ/m^3/K$)		
		HD	SP	HD-SP	HD	SP	HD-SP	HD	SP	HD-SP
KFM01A-90V-11	50	3.70	3.67	–0.03	1.51	1.50	–0.01	2.45	2.45	0.00
KFM01A-90V-12	50	3.65	3.58	–0.08	1.49	1.45	–0.04	2.45	2.47	0.02
KFM01A-90V-13	50	3.58	3.49	–0.09	1.48	1.48	–0.01	2.42	2.36	–0.05
KFM01A-90V-14	50	3.67	3.76	0.09	1.52	1.47	–0.05	2.42	2.56	0.14
KFM01A-90V-15	50	3.69	3.69	0.00	1.50	1.58	0.09	2.46	2.33	–0.13
KFM01A-90V-16	50	3.68	3.57	–0.12	1.64	1.66	0.02	2.25	2.15	–0.10
KFM01A-90V-17	50	3.65	3.69	0.05	1.53	1.45	–0.08	2.39	2.55	0.16
KFM01A-90V-18	50	3.54	3.55	0.01	1.64	1.61	–0.03	2.16	2.21	0.05
KFM01A-90V-19	50	3.58	3.53	–0.05	1.54	1.55	0.01	2.33	2.29	–0.05
KFM01A-90V-20	50	3.81	3.88	0.07	1.59	1.57	–0.02	2.39	2.47	0.08
Mean value		3.65	3.64	–0.01	1.54	1.53	–0.01	2.37	2.38	0.01
Standard deviation		0.08	0.12	0.07	0.06	0.07	0.05	0.10	0.14	0.10
Upper 95% confidence level		3.72	3.74	0.04	1.59	1.59	0.03	2.45	2.50	0.10
Lower 95% confidence level		3.59	3.54	–0.07	1.49	1.47	–0.05	2.29	2.27	–0.07

Table 5-15. Results from testing the thermal properties at 80°C at SP and Hot Disk (HD) on paired samples from KSH01A.

Sample identification	Test temperature (°C)	Thermal Conductivity (W/m/K) HD	SP	HD-SP	Thermal Diffusivity (mm^2/s) HD	SP	HD-SP	Heat Capacity ($MJ/m^3/K$) HD	SP	HD-SP
KSH01A-90V-1	80	2.76	2.73	–0.03	1.06	1.06	0.00	2.61	2.58	–0.03
KSH01A-90V-2	80	2.8	2.79	–0.01	1.05	1.04	–0.01	2.67	2.70	0.03
KSH01A-90V-3	80	2.77	2.75	–0.02	1.08	1.06	–0.02	2.58	2.61	0.03
KSH01A-90V-4	80	2.83	2.79	–0.04	1.14	1.07	–0.07	2.47	2.61	0.14
KSH01A-90V-5	80	2.83	2.76	–0.07	1.11	1.15	0.04	2.56	2.39	–0.17
KSH01A-90V-7	80	2.7	2.71	0.01	1.09	1.04	–0.05	2.48	2.60	0.12
KSH01A-90V-9	80	3.01	2.96	–0.05	1.12	1.11	–0.01	2.67	2.66	–0.01
KSH01A-90V-10	80	2.82	2.77	–0.05	1.12	1.11	–0.01	2.52	2.50	–0.02
KSH01A-90V-11	80	2.72	2.72	0.00	1.01	1.01	0.00	2.7	2.69	–0.01
Mean value		2.80	2.78	–0.03	1.09	1.07	–0.02	2.58	2.60	0.01
Standard deviation		0.09	0.07	0.03	0.04	0.04	0.03	0.08	0.10	0.09
Upper 95% confidence level		2.89	2.84	0.00	1.12	1.11	0.01	2.66	2.68	0.09
Lower 95% confidence level		2.72	2.71	–0.05	1.05	1.03	–0.05	2.51	2.51	–0.07

Table 5-16. Results from testing the thermal properties at 80°C at SP and Hot Disk (HD) on paired samples from KFM01A.

Sample identification	Test temperature (°C)	Thermal Conductivity (W/m/K) HD	SP	HD-SP	Thermal Diffusivity (mm^2/s) HD	SP	HD-SP	Heat Capacity ($MJ/m^3/K$) HD	SP	HD-SP
KFM01A-90V-11	80	3.50	3.62	0.12	1.36	1.34	–0.03	2.57	2.71	0.14
KFM01A-90V-12	80	3.42	3.49	0.08	1.37	1.28	–0.09	2.50	2.74	0.24
KFM01A-90V-13	80	3.37	3.33	–0.04	1.30	1.41	0.11	2.59	2.36	–0.23
KFM01A-90V-14	80	3.42	3.62	0.20	1.38	1.36	–0.03	2.48	2.67	0.19
KFM01A-90V-15	80	3.51	3.61	0.10	1.36	1.30	–0.06	2.58	2.77	0.19
KFM01A-90V-16	80	3.45	3.50	0.05	1.47	1.35	–0.12	2.35	2.60	0.25
KFM01A-90V-17	80	3.37	3.61	0.24	1.36	1.28	–0.08	2.47	2.82	0.35
KFM01A-90V-18	80	3.37	3.44	0.07	1.47	1.45	–0.02	2.30	2.38	0.08
KFM01A-90V-19	80	3.39	3.45	0.06	1.38	1.35	–0.03	2.46	2.55	0.10
KFM01A-90V-20	80	3.57	3.71	0.15	1.46	1.45	–0.01	2.44	2.56	0.12
Mean value		3.44	3.54	0.10	1.39	1.36	–0.04	2.47	2.62	0.14
Standard deviation		0.07	0.11	0.08	0.06	0.06	0.06	0.10	0.16	0.15
Upper 95% confidence level		3.50	3.64	0.17	1.44	1.41	0.02	2.55	2.75	0.27
Lower 95% confidence level		3.38	3.44	0.03	1.34	1.30	–0.09	2.39	2.48	0.01

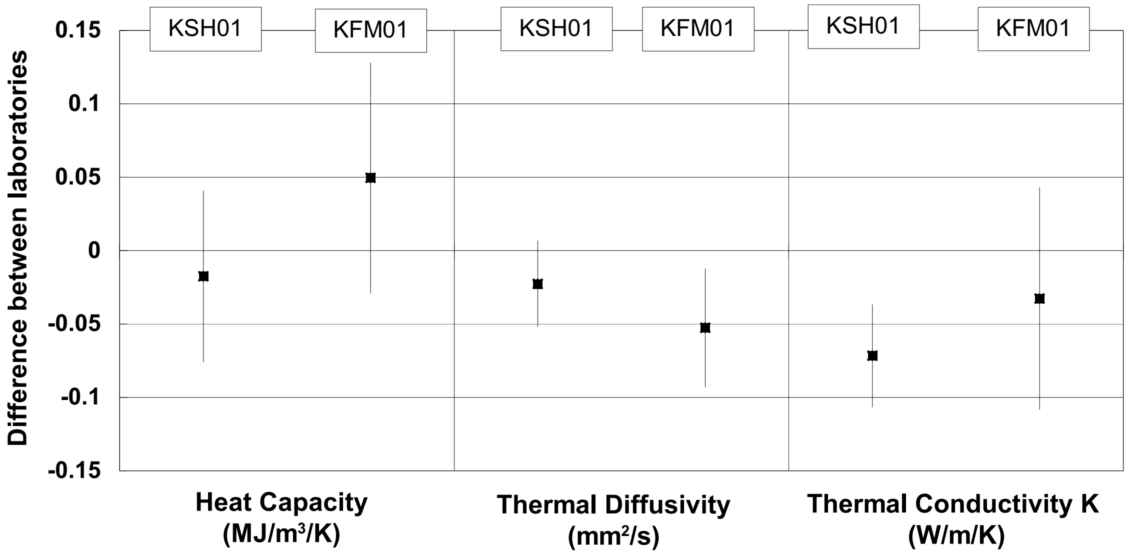

Figure 5-15. *Diagram showing the measurements of thermal properties at 20°C of samples from KSH01A and KFM01A at the two laboratories. The diagram illustrates the difference and 95% confidence interval of the mean value of the difference between the laboratories.*

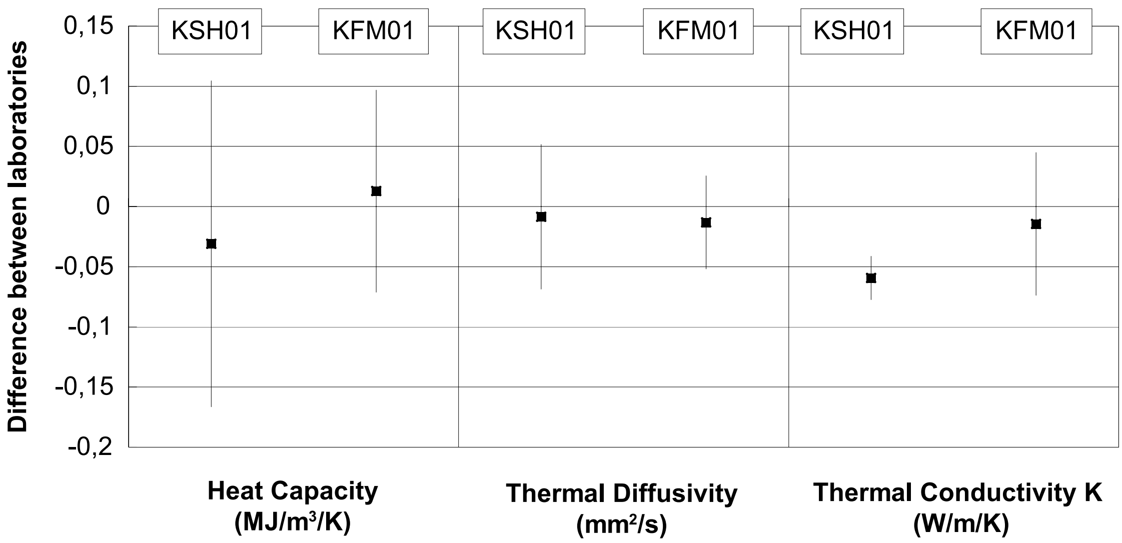

Figure 5-16. *Diagram showing the measurements of thermal properties at 50°C of samples from KSH01A and KFM01A at the two laboratories. The diagram illustrates the difference and 95% confidence interval of the mean value of the difference between the laboratories.*

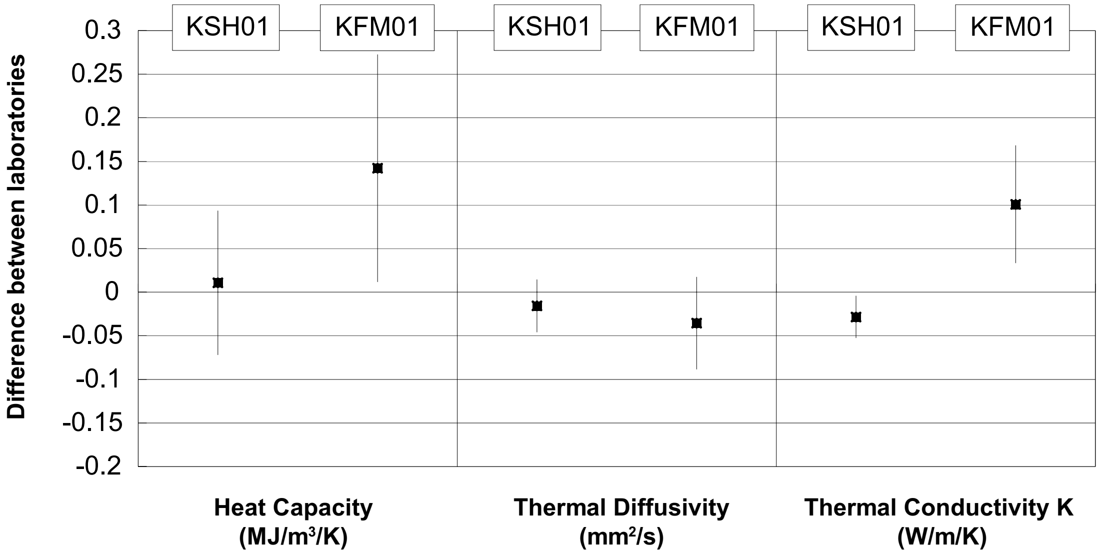

Figure 5-17. Diagram showing the measurements of thermal properties at 80°C of samples from KSH01A and KFM01A at the two laboratories. The diagram illustrates the difference and 95% confidence interval of the mean value of the difference between the laboratories.

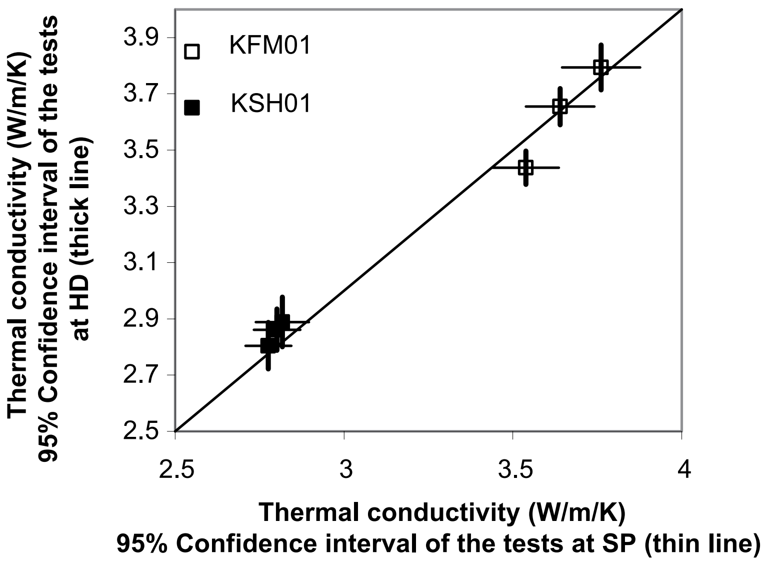

Figure 5-18. Diagram showing the measurements of thermal conductivity. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured thermal conductivity at HD and SP, respectively. The point where the lines cross illustrates the mean values of the laboratories. The diagonal line shows where the cross should be if the results from the laboratories were the same.

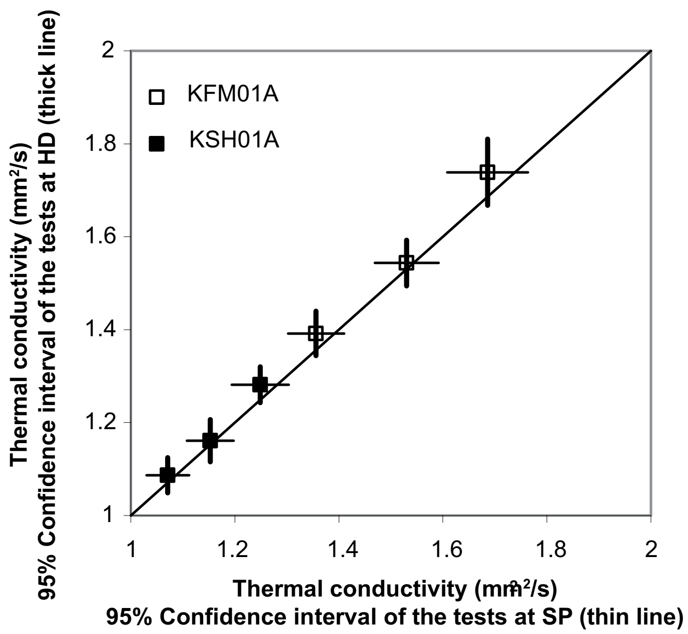

Figure 5-19. *Diagram showing the measurements of thermal diffusivity. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured thermal conductivity at HD and SP, respectively. The point where the lines cross illustrates the mean values of the laboratories. The diagonal line shows where the cross should be if the results from the laboratories were the same.*

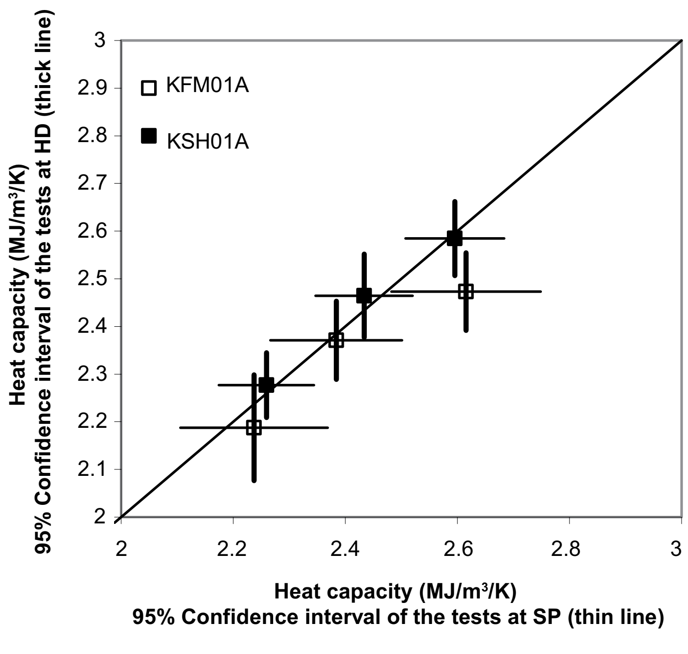

Figure 5-20. *Diagram showing the measurementst of heat capacity. The length of the horizontal and vertical lines describes the length of the confidence interval of the measured heat capacity at HD and SP, respectively. The point where the lines cross illustrates the mean values of the laboratories. The diagonal line shows where the cross should be if the results from the laboratories were the same.*

The differences between the laboratories shown in Figures 5-15 to 5-20 are very small and are in the range of the uncertainty of the method, about 0.005-0.10.

6 Discussion and conclusions

The intention of this investigation was to evaluate the differences in rock mechanics and thermal test results, both within and between the laboratories making the measurements. For each method samples from two boreholes were tested at two different laboratories.

In some cases, i.e. for the non-destructive tests, it was possible to use the same samples at the two laboratories: this was the case for testing heat capacity, thermal diffusivity, thermal conductivity and thermal expansion. These samples were first tested at SP and then tested at the alternative laboratory. In the ideal case, the results from the laboratories should be the same; any difference between the results would be a function of the individual laboratory's procedure, and it was assumed that the fact that the SP testing occurred first was not significant.

The remaining methods are all destructive methods. For these cases, the samples were chosen to have a low variability. In this way, the minimum difference that would occur is the natural variation between the samples. So, the more homogenous the sample sets, the better the agreement should be between the laboratories, although a certain degree of variability will be inevitable, commensurate with the sample set variability.

The numbers of laboratories and samples (borehole and samples from each borehole) are insufficient to perform a complete statistical analysis of the variation between the samples compared to the repeatability and reproducibility of the methods. The difference between the mean values from the laboratories is, however, a measure of the reproducibility; the variation in the laboratories is an indicative measure of the repeatability (which includes the variation of the samples).

The results from this investigation can be divided into three categories: no significant difference; significant difference; and doubtful significance. In the following cases, no significant difference between the laboratories could be detected and the variation of the results can be considered as an indicative measure of the precision of the methods. Also, since the results are in agreement, they can be considered accurate (unless the testing method itself is flawed).

No significant difference between laboratories	• thermal capacity • thermal diffusivity • thermal conductivity • compressive strength via the uniaxial strength test

In the following cases a significant difference between the laboratories was detected. The within-laboratory variation is, however, an indicative measure of the repeatability.

In the following cases, the significance of the difference between the laboratories is doubtful.

Questionable difference between laboratories	• Young's modulus • Residual shear stress • Indirect tensile strength test

To estimate the precision of the methods, the reason for the differences above needs to be investigated further. This is, however, not a part of the current commission, although interviews with responsible personnel at the SP laboratories indicated that the following potential reasons could be noted.

- Load application (interlayer) in the indirect tensile strength test.
- Shear area and compensation for change of area during the shear test.
- Stress level for calculation of the Poisson's ratio.
- Conversion of readings for measuring thermal expansion.

Before any further investigation is performed, these differences between the laboratories must be examined further and eliminated.

It is rare in site investigation and even in research rock mechanics testing for these kinds of quality checks to be conducted, despite the fact that for both applications it may well be crucial that accurate and precise results are achieved. Thus, it is certainly encouraging that many of the inter-laboratory comparisons provided positive results, indicating that the sampling, testing and data reduction were all carried out well.

For example, the results in Figure 5-1 could hardly be better, apart from the spread in results for the KFM01A compressive strengths, but this could have been a result of the natural sample variability for that suite of tests. Similarly, the results in Figure 5-2 for Young's modulus indicate the testing accuracy and the rock variation for the KSH01 core samples. Also, the tensile strength results in Figure 5-7 are strongly in agreement with just some deviation for the KFM01A results. The results for peak shear stress in Figure 5-8 show a consistent bias – which reflects a problem in the shear testing, which is notoriously difficult. It has already been noted that the factor of four in the thermal expansion tests is the likely explanation for the differences summarised in Figure 5-14. Finally, the results shown in Figures 5-14 to 5-20 for the thermal conductivity, thermal diffusivity and heat capacity, respectively, are in excellent agreement.

For future inter-laboratory comparisons of this nature, we recommend that the technically responsible staff at the laboratories scrutinize the methods and the procedures (sample preparation, testing and data reduction) together, in order to identify and take care of the differences between laboratories. The thermal properties are measured by the same principle on equipment from the same deliverer. It could therefore be of interest to compare the results with the results that are obtained by another principle measurements.

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