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Forsmark site investigation

Determination of the direct and indirect tensile strength on cores from borehole KFM01D

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Abstract

Twenty direct and fourty Brazilian tensile strength tests on intact rock specimens were conducted in this test program. The specimens were collected at two depth levels ranging between 386–400 m in borehole KFM01D. The rock type in all specimens were granite to granodiorite, metamorphic, medium-grained (101057).

The measured wet densities for the rock specimens sampled in borehole KFM01D were in the range 2,630–2,660 kg/m^3. The values for direct and Brazilian (indirect) tensile strength were in the range 7,9–13,2 MPa and 15,5–22,1 MPa respectively.

The direct tensile test yielded lower strength values than the Brazilian test as the direct tensile test is affected to a greater degree by the presence of microfractures and microfissures in the rock. The rock fails according to the 'weakest link'. For the specimens tested in direct tension, failure occurred on a plane within the neck and perpendicular to the axis of the core. The higher Brazilian tensile strength results may be attributed to the combination of compressive and tensile stresses imposed on the rock using this test method. The compressive force must overcome the frictional forces at shearing grains or grain boundaries in order to initiate tensile failure.

Sammanfattning

Tjugo direkt och fyrtio Brazilian (indirekt) draghållfasthetstester, σ_t, har utförts på intakta kärnprover och redovisas i denna rapport. Bergproverna har tagits från två olika nivåer som ligger mellan 386–400 m (borrhålslängd) i kärnborrhålet KFM01D. Bergarten för alla prov var granit till granodiorit, metamorfisk, medelkornig (101057).

Densiteten hos de vattenmättade proverna var mellan 2 630–2 660 kg/m^3. Värdena på den direkta och Brazilian (indirekta) draghållfastheten var 7,9–13,2 MPa respektive 15,5–22,1 MPa.

Den direkta draghållfastheten erhöll lägre värden än proverna för indirekta draghållfastheten då provkroppen är exponerad för en större mängd mikrosprickor och mikrofissurer. Brottet på provkroppen sker vid dess svagaste länk. Vid direkta draghållfastetsförsök skedde brottet längs en rak linje vid provkroppens midja och vinkelrätt mot borrkärnans axel. De högre värdena erhållna vid indirekta draghållfasthetsförsök kan bero på kombinationen av tryck- och dragspänningar som verkar på provkroppen vid användandet med denna testmetod. Tryckkraften måste överstiga friktionskraften i bergprovets skjuvkorn eller dess korngränser för att draghållfasthetsbrott ska vara möjlig.

Contents

1   Introduction

This document reports performance and results of both direct and indirect (Brazilian) tensile strength test methods, on water-saturated drill core specimens sampled from borehole KFM01D at Forsmark, see map in Figure 1-1. The tests were carried out in the CANMET Mining and Mineral Sciences Laboratories in Ottawa, Canada, at their Rock Mechanics test facility located in Bells Corners. The activity is part of the site investigation programme at Forsmark managed by SKB (The Swedish Nuclear Fuel and Waste Management Company).

The controlling documents for the activity are listed in Table 1-1. The Activity Plan is SKB's internal controlling document, whereas the Quality Plan referred to in the table is an SP internal controlling document.

Borehole KFM01D, see Figure 1-1, is a telescopic drilled borehole inclined c 55° from the horizontal plane with bearing 35° and with a total length of c 800 m.

SKB supplied CANMET with rock cores which arrived at CANMET in June 2006. Cylindrical specimens were cut from the cores and selected based on the drill core logging with the strategy to primarily investigate the properties of the rock type granite to granodiorite, metamorphic, medium-grained (101057).

Table 1-1. Controlling documents for the performance of the activity.

Activity Plan	Number	Version
Determination of the direct and indirect tensile strength on cores from borehole KFM01D.	AP PF 400-06-067	1.0
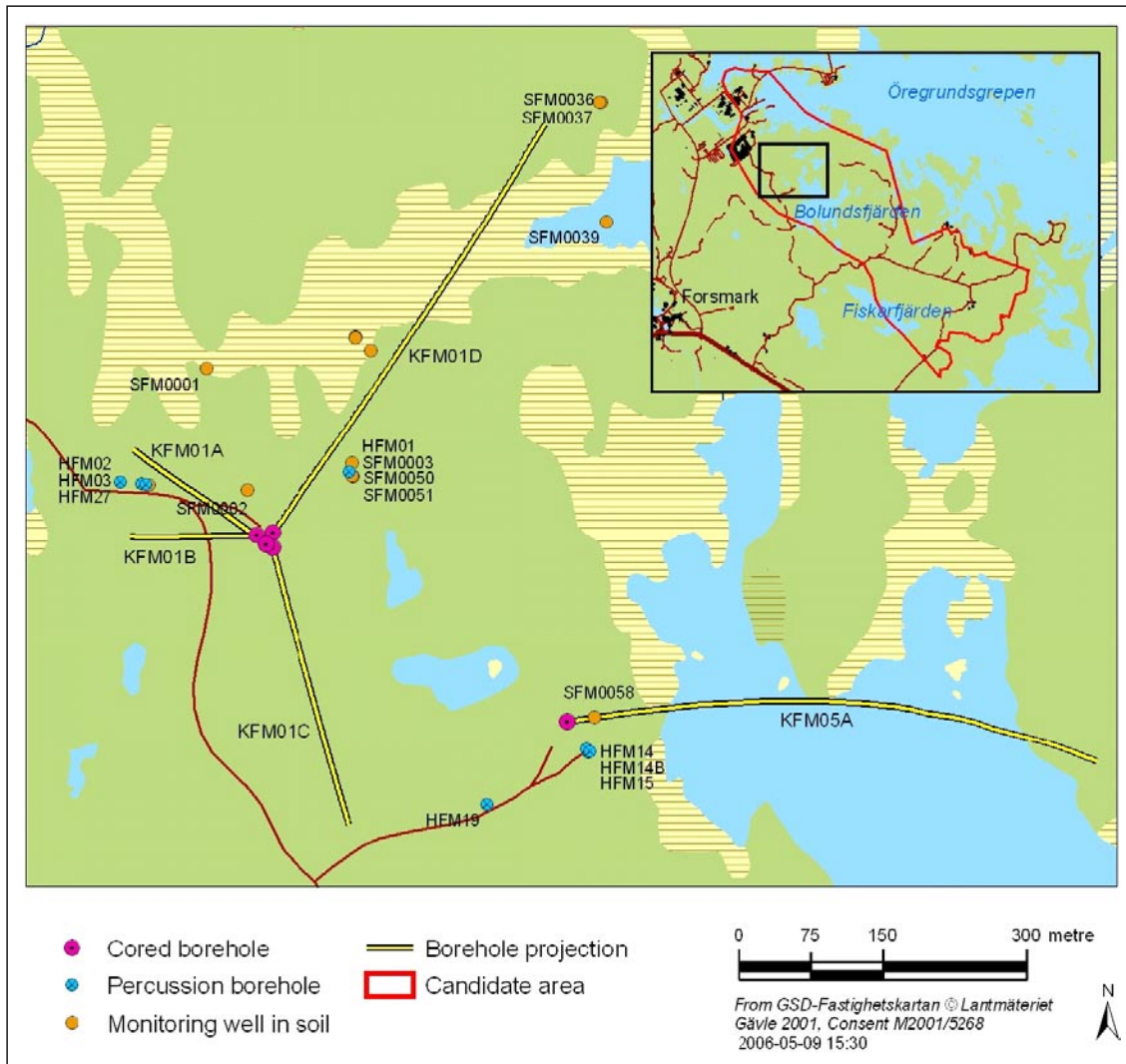
Figure 1-1. *The Forsmark candidate area, illustrating the location of drill sites no. 1 and 5, (the black square in the small, enclosed map). The large map displays the location and projection on the ground surface of the borehole, KFM01D, from which drill cores will be tested for determination of direct and indirect tensile strength, as well as nearby situated core- and percussion drilled boreholes and monitoring wells in soil.*

2   Objective and scope

One major issue within the programme for rock mechanics at the Forsmark site in Sweden, is an investigation strategy aiming at an overall understanding of the state of stress. In situ stress measurements have been carried out in a number of boreholes with both overcoring and hydraulic methods. During recent site investigation drilling by SKB at Forsmark, to depths of 1,000 m localized core disking was encountered. The rock type is primarily granite to granodiorite. The results of a series of analyses indicate that core disking can be used to constrain the stress magnitudes but that the tensile strength can have a significant impact on the stress magnitudes determined from core disking /Lim and Martin 2006/. Knowing the representative tensile strength is important in constraining the stress magnitudes.

SKB contracted the CANMET-MMSL Rock Mechanics Laboratory to undertake 'dogbone' shaped direct tensile tests on rock specimens from borehole KFM01D. The tests were requested to determine both the direct and indirect or Brazilian tensile strength of the rock core. Densities and dynamic constants were also determined as standard laboratory practice.

In addition, various studies of indirect stress observations, such as borehole breakouts and core disking have been initiated. Data from the present report will be used in a study on core disking carried out at the University of Alberta, Canada.

3   Equipment

3.1   Description of equipment

The following equipment were mainly used to prepare and to perform tensile strenght tests:

- Lathe Tool-Post Grinder.
- Split-Grip Direct Tensile Strength Test Assembly.
- Split-Grip Direct Tensile Strength Test Assembly set up in MTS Test System.
- Indirect Tensile Strength Test Assembly set up in MTS Test System.

4   Execution

The determination of the indirect and indirect tensile strength were carried out in compliance with the Activity Plan (SKB internal controlling document) and ASTM standard test methods, see below.

4.1   Description of the specimens

The rock type characterisation was made according to /Stråhle 2001/ using the SKB mapping system (Boremap). The rock type was granite to granodiorite, metamorphic, medium-grained (101057).

4.2   Test procedure

The test program was contracted to the CANMET Mining and Mineral Sciences Laboratories in Ottawa, Canada. Actual testing was carried out at the Rock Mechanics test facility located in Bells Corners. The Rock Mechanics test facility is managed by the Ground Control Program. The test facility is an ISO 17025 (International Standards Organization) accredited testing laboratory. Standard Operating Procedures (SOPs) that form part of the facility's accredited test procedures were selected for this project.

The Standard Operating Procedures used for this test program were:

SOP-T 2100 Specimen Preparation, Standardization and Dimensional Tolerance Verification,

SOP-T 2103 Compressional P-Wave Velocity Test,

SOP-T 2104 Brazilian Tensile Strength Test, and

SOP-T 2105 Direct Tensile Strength Test.

All specimens were cut and lapped to within specified tolerances, weighed and dimensioned /ASTM D4543 2004/. Prior to undertaking 'dogbone' preparation procedures, the depths, dimensions, mass and bulk density of each specimen were measured and calculated. The results of these measurements are listed in Table 4-1. Velocity measurements were also determined and are shown recorded in Table 4-2 /ASTM D2845 2005/. Twenty direct tensile 'dogbone' specimens were contoured using a machinist's lathe equipped with a tool post grinder (Figure 4-1). The grinder was equipped with a diamond impregnated grinding wheel.

Figure 4-1. *Grinding Specimen with Lathe Tool-Post Grinder.*

The tests were performed using an MTS 815 Test System equipped with a tensile apparatus. The patented tensile apparatus (USA patent 5,193,396), was designed and fabricated by CANMET-MMSL to accommodate tensile testing using a compression press /Gorski and Yu 1996/. The compression of the apparatus in the press transmits direct tension in the rock specimen. Figure 4-2 illustrates the disassembled split grip tensile apparatus. The split grip shoulder mates the shoulder of the rock test specimen thereby allowing the rock to be pulled apart. The split grip pairs, placed on the cylindrical ends of the rock specimen are threaded, as a unit, into the grip collars.

Once the grip collars are threaded on, a pipe, having two holes at the top, is installed over the assembled rock specimen (samples A and C, see Table 5-1). A hole through the bottom grip collar is aligned with two matching holes of the pipe and then a resisting steel pin is slid into place. A hole through the top grip collar is aligned 90° to the bottom grip collar hole. A resisting steel pin is then slid through the two slotted holes drilled through the upper part of the steel pipe and through the top grip collar hole. The assembled sample together with the sleeve are then lowered into a larger diameter pipe and suspended on it by the upper pin bearing on two half slotted holes located at the top of the outer pipe. The apparatus is self-aligning under load. The assembled tensile apparatus is then installed on the MTS Test System load cell (Figure 4-3). Figure 4-4 shows the MTS Test System used for the indirect tensile strength tests.

Two Brazilian tensile test specimens were prepared from the ends of each of the tested 'dog-bone' direct tensile specimens. Direct tensile and Brazilian tensile tests were loaded in stress control to imminent failure at a rate of 0.75 MPa/s using the MTS 815 Rock Mechanics Test System /ASTM D2936 2004, ATM D3967 2005/.

Figure 4-2. *Split-Grip Direct Tensile Strength Test Assembly (typical).*

Figure 4-3. Split-Grip Direct Tensile Strength Test Assembly set up in MTS Test System.
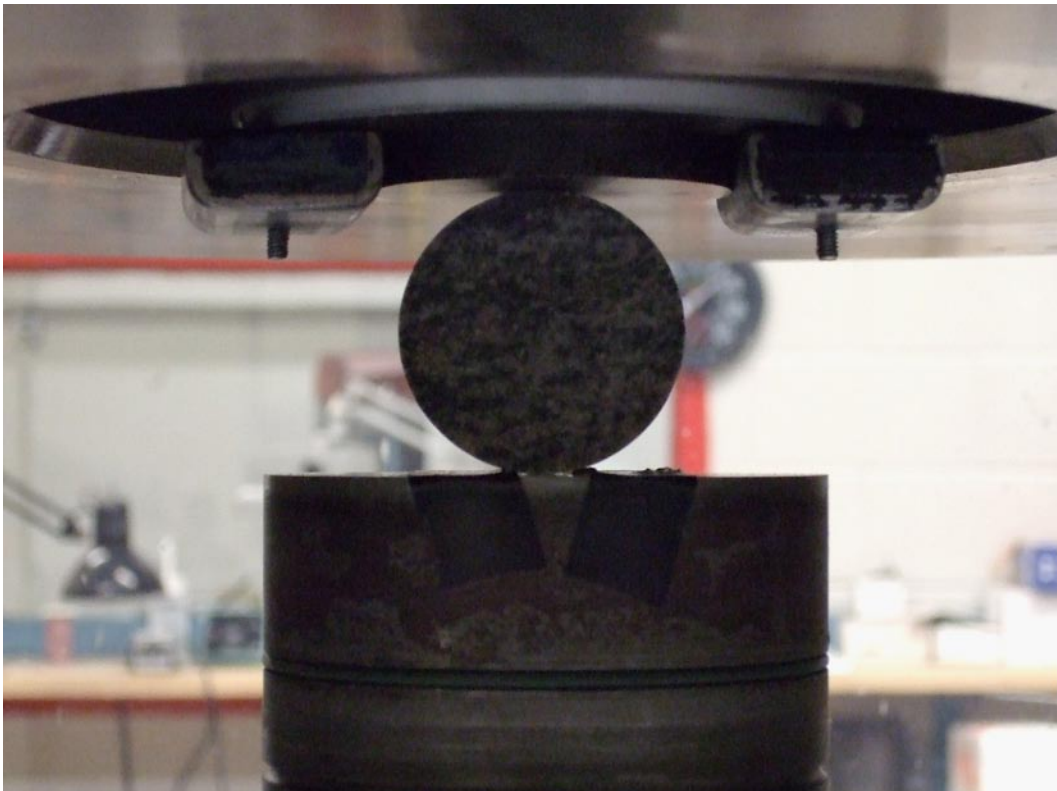
Figure 4-4. Direct Tensile Strength Test Assembly set up in MTS Test System.

Table 4-1. Borehole KFM01D Specimen Selection Data.

Sec Up Depth (m)	Mass (g)	Length (mm)	Diameter (mm)	Density (Mg/m³)
386.92	668.78	127.35	50.38	2.63
387.05	670.71	127.34	50.35	2.65
387.19	670.64	127.34	50.35	2.64
387.33	670.60	127.25	50.36	2.65
387.46	671.30	127.32	50.36	2.65
387.59	671.27	127.29	50.35	2.65
387.79	670.70	127.14	50.37	2.65
387.87	671.03	127.15	50.34	2.65
388.05	671.86	127.22	50.34	2.65
388.18	672.82	127.28	50.34	2.66
388.52	673.09	127.32	50.33	2.66
388.66	672.27	127.31	50.34	2.65
388.79	672.11	127.26	50.35	2.65
388.93	672.34	127.24	50.33	2.66
399.18	670.23	127.27	50.35	2.65
399.32	671.86	127.39	50.36	2.65
399.45	670.74	127.23	50.35	2.65
399.58	671.69	127.29	50.34	2.65
399.72	671.93	127.36	50.35	2.65
399.85	672.50	127.40	50.36	2.65

Table 4-2. Dynamic Constants.

Sec Up Depth (m)	P-wave Velocity (km/s)	S-wave Velocity (km/s)	Young's Modulus (MPa)	Shear Modulus (GPa)	Poisson's Ratio
386.92	5.09	3.18	63.00	26.71	0.18
387.05	5.13	3.18	63.70	26.81	0.19
387.19	5.05	3.15	62.09	26.28	0.18
387.33	5.01	3.13	61.25	25.99	0.18
387.46	4.97	3.08	59.61	25.04	0.19
387.59	4.97	3.09	59.95	25.28	0.19
387.79	4.93	3.04	58.41	24.50	0.19
387.87	5.05	3.15	62.06	26.26	0.18
388.05	5.01	3.10	60.72	25.54	0.19
388.18	5.05	3.17	62.64	26.63	0.18
388.52	5.13	3.17	63.59	26.65	0.19
388.66	5.13	3.18	63.84	26.87	0.19
388.79	5.17	3.23	65.35	27.68	0.18
388.93	5.21	3.26	66.63	28.27	0.18
399.18	5.05	3.15	62.04	26.25	0.18
399.32	5.02	3.08	60.08	25.07	0.20
399.45	5.17	3.18	64.08	26.79	0.20
399.58	5.13	3.18	63.78	26.85	0.19
399.72	5.09	3.18	63.37	26.86	0.18
399.85	5.06	3.17	62.62	26.62	0.18

Table 4-3. Specimen Dimensions.

Sec Up Depth (m)	Direct Tensile (B) Diameter (mm)	Length (mm)	Brazilian (A) Diameter (mm)	Length (mm)	Brazilian (C) Diameter (mm)	Length (mm)
386.92	38.16	76.84	50.34	16.73	50.35	27.34
387.05	38.21	76.56	50.35	24.31	50.34	24.62
387.19	38.06	76.37	50.33	23.63	50.34	24.99
387.33	38.08	76.33	50.35	24.63	50.35	25.83
387.46	38.12	76.30	50.36	25.10	50.37	25.17
387.59	38.18	76.34	50.34	24.88	50.36	25.17
387.79	38.16	76.31	50.33	24.81	50.32	25.32
387.87	38.15	76.29	50.36	25.11	50.36	24.98
388.05	38.22	76.52	50.35	24.78	50.34	24.86
388.18	38.08	76.69	50.36	25.63	50.36	24.08
388.52	38.26	76.62	50.34	25.01	50.34	25.20
388.66	38.16	76.60	50.34	25.20	50.34	25.61
388.79	38.17	76.43	50.34	24.93	50.34	25.21
388.93	38.12	76.31	50.34	25.16	50.36	24.86
399.18	38.23	76.31	50.32	20.82	50.33	25.31
399.32	38.21	76.32	50.31	24.77	50.33	25.69
399.45	38.24	76.27	50.32	24.87	50.30	25.51
399.58	38.22	76.46	50.32	24.50	50.34	25.80
399.72	38.19	76.72	50.35	24.80	50.34	22.74
399.85	38.17	76.38	50.33	25.03	50.34	24.26

4.3   Nonconformities

The direct and indirect tensile strength tests were conducted according to the Activity Plan.

5 Results

The results were reported to the SICADA database, where they are traceable by the Activity Plan number. The handling of the results follows SDP-508 (SKB internal controlling document) in general.

Twenty direct and fourty Brazilian tensile strength tests were conducted in this test program. The obtained results are listed in Table 5-1. The direct tensile strengths of the 'dogbone' specimens were calculated using the following formula:

Direct Tensile Strength $\sigma_t = P/A$ (MPa)

where

P = load at failure (N)

A = cross-sectional area at neck failure zone (mm²)

Brazilian Tensile Strengths were calculated using the following formula:

Brazilian Tensile Strength $\sigma_t = 2P/\pi Dt$ (MPa)

where

P = load at failure (N)

D = diameter (mm)

t = thickness (mm)

Table 5-1. Tensile Strength Results.

Specimen Depth (m)	Direct Tensile (B) Failure Load (N)	σ_t (MPa)	Brazilian (A) Failure Load (N)	σ_t (MPa)	Brazilian (C) Failure Load (N)	σ_t (MPa)
386.92	9,031	−7.90	25,749	−19.46	43,503	−20.12
387.05	14,840	−12.94	38,260	−19.90	40,468	−20.79
387.19	14,511	−12.76	39,136	−20.95	39,929	−20.21
387.33	13,541	−11.89	43,040	−22.09	41,665	−20.40
387.46	9,874	−8.65	40,654	−20.48	38,285	−19.22
387.59	11,645	−10.17	41,859	−21.28	36,767	−18.47
387.79	12,985	−11.35	39,946	−20.37	37,037	−18.51
387.87	15,118	−13.23	39,212	−19.74	37,846	−19.15
388.05	14,224	−12.40	35,730	−18.23	39,844	−20.27
388.18	14,317	−12.57	38,757	−19.12	34,955	−18.35
388.52	11,940	−10.39	40,426	−20.44	36,843	−18.49
388.66	14,183	−12.40	40,966	−20.56	39,044	−19.28
388.79	13,829	−12.09	38,917	−19.74	41,657	−20.90
388.93	12,286	−10.77	34,306	−17.24	39,735	−20.21
399.18	9,790	−8.53	29,298	−17.80	30,967	−15.48
399.32	13,340	−11.63	35,688	−18.23	36,068	−17.76
399.45	11,038	−9.61	34,002	−17.30	31,709	−15.73
399.58	12,623	−11.00	35,747	−18.46	37,712	−18.49
399.72	11,696	−10.21	35,208	−17.95	33,244	−18.49
399.85	12,328	−10.77	36,818	−18.61	36,135	−18.84

The direct tensile test yielded lower strength values than the Brazilian test as the direct tensile test is affected to a greater degree by the presence of microfractures and microfissures in the rock. The rock fails according to the 'weakest link'. For the specimens tested in direct tension, failure occurred on a plane within the neck and perpendicular to the axis of the core. The higher Brazilian tensile strength results may be attributed to the combination of compressive and tensile stresses imposed on the rock using this test method. The compressive force must overcome the frictional forces at shearing grains or grain boundaries in order to initiate tensile failure.

The measured wet densities for the rock specimens sampled in borehole KFM01D were in the range 2,630–2,660 kg/m^3. The values for direct and Brazilian (indirect) tensile strength were in the range 7,9–13,2 MPa and 15,5–22,1 MPa respectively. The densities and tensile strength versus sampling depth are shown in Figures 5-1 and 5-2.
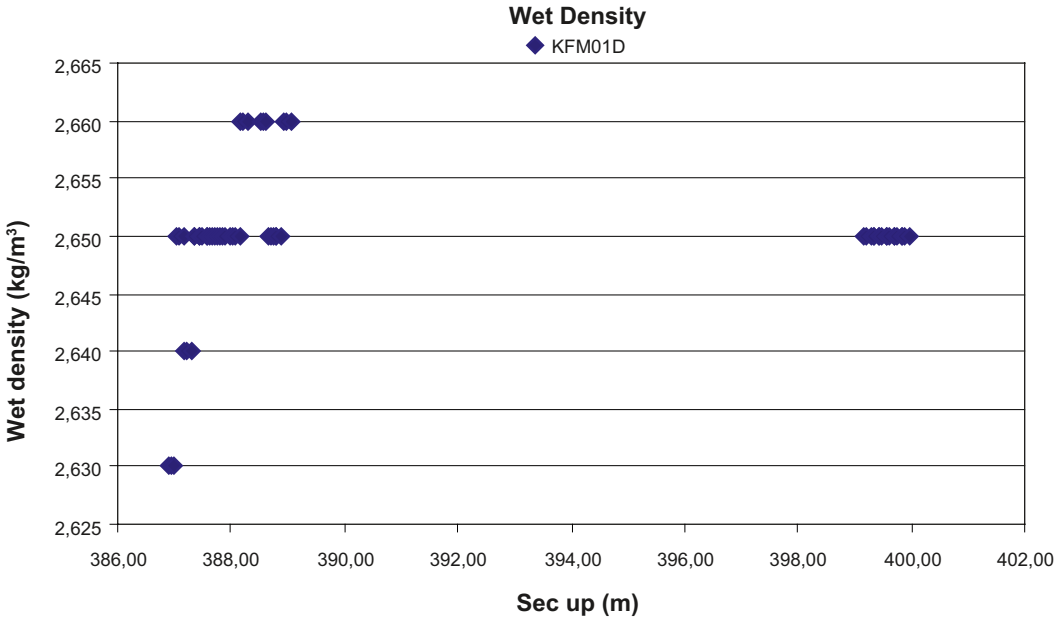

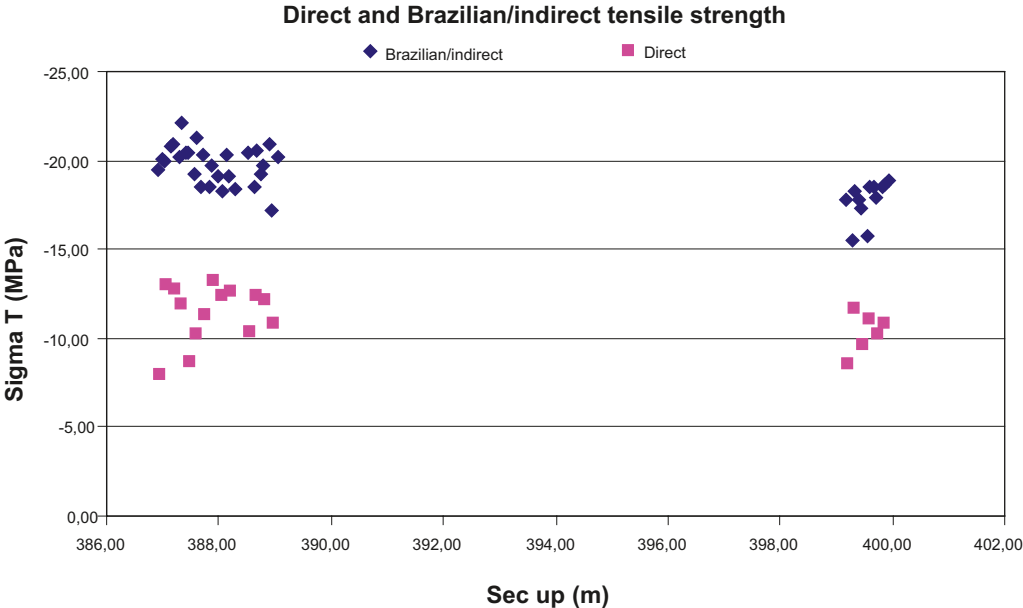**Figure 5-1.** *Density versus sampling depth in boreholes.*

Figure 5-2. *Direct and Brazilian Tensile strength versus sampling depth in boreholes.*

References

ASTM D4543, 2004. Standard Practice for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances; Annual Book of ASTM Standards, Vol. 04.08.

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Direct and Brazilian Tensile Strength of Rock from Forsmark, Sweden

Fiscal year: 2006

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Executive summary

Drill core specimens of a granodiorite rock unit were received from Svensk Kärnbränslehantering AB (SKB). The purpose of the test program was to provide SKB with tensile strength values using both the direct and Brazilian tensile strength test methods.

Table of contents

Figures no.

Tables no.

Introduction

CANMET MMSL received from Svensk Kärnbränslehantering AB better known as SKB, rock core samples originating from Forsmark, Sweden. SKB is owned by four power companies and is tasked with managing and disposing of radioactive waste from the Swedish nuclear power.

Sweden's final disposal site for radioactive operational waste (SFR) is located in Forsmark. During recent site investigation drilling by SKB at Forsmark, Sweden, to depths of 1,000 m localized core disking was encountered. The rock type is primarily granodiorite. The results of a series of analyses indicate that core disking can be used to constrain the stress magnitudes but that the tensile strength can have a significant impact on the stress magnitudes determined from core disking /Lim and Martin 2006/. Knowing the representative tensile strength is important in constraining the stress magnitudes.

SKB contracted the CANMET-MMSL Rock Mechanics Laboratory to undertake 'dogbone' shaped direct tensile tests on rock specimens. The tests were requested to determine both the direct and indirect or Brazilian tensile strength of the rock core. Densities and dynamic constants were also determined as standard laboratory practice.

Test procedure

The test program was contracted to the CANMET Mining and Mineral Sciences Laboratories in Ottawa. Actual testing was carried out at the Rock Mechanics test facility located in Bells Corners. The Rock Mechanics test facility is managed by the Ground Control Program. The test facility is an ISO 17025 (International Standards Organization) accredited testing laboratory. Standard Operating Procedures (SOPs) that form part of the facility's accredited test procedures were selected for this project.

The Standard Operating Procedures used for this test program were:

SOP-T 2100 Specimen Preparation, Standardization and Dimensional Tolerance Verification,

SOP-T 2103 Compressional P-Wave Velocity Test,

SOP-T 2104 Brazilian Tensile Strength Test, and

SOP-T 2105 Direct Tensile Strength Test.

The test specimens originated from Borehole KFM 01D. All specimens were cut and lapped to within specified tolerances, weighed and dimensioned /ASTM D4543 2004/. Prior to undertaking 'dogbone' preparation procedures, the depths, dimensions, mass and bulk density of each specimen were measured and calculated. The results of these measurements are listed in Table 1. Velocity measurements were also determined and are shown recorded in Table 2 /ASTM D2845 2005/. Twenty direct tensile 'dogbone' specimens were contoured using a machinist's lathe equipped with a tool post grinder (Figure 1). The grinder was equipped with a diamond impregnated grinding wheel.


Figure 1. *Grinding Specimen with Lathe Tool-Post Grinder.*

The tests were performed using an MTS 815 Test System equipped with a tensile apparatus. The patented tensile apparatus (USA patent 5,193,396), was designed and fabricated by CANMET – MMSL to accommodate tensile testing using a compression press /Gorski and Yu 1996/. The compression of the apparatus in the press transmits direct tension in the rock specimen. Figure 2 illustrates the disassembled split grip tensile apparatus. The split grip shoulder mates the shoulder of the rock test specimen thereby allowing the rock to be pulled apart. The split grip pairs, placed on the cylindrical ends of the rock specimen are threaded, as a unit, into the grip collars.

Once the grip collars are threaded on, a pipe, having two holes at the top, is installed over the assembled rock specimen. A hole through the bottom grip collar is aligned with two matching holes of the pipe and then a resisting steel pin is slid into place. A hole through the top grip collar is aligned 90° to the bottom grip collar hole. A resisting steel pin is then slid through the two slotted holes drilled through the upper part of the steel pipe and through the top grip collar hole. The assembled sample together with the sleeve are then lowered into a larger diameter pipe and suspended on it by the upper pin bearing on two half slotted holes located at the top of the outer pipe. The apparatus is self-aligning under load. The assembled tensile apparatus is then installed on the MTS Test System load cell (Figure 3).

Figure 2. *Split-Grip Direct Tensile Strength Test Assembly (typical).*
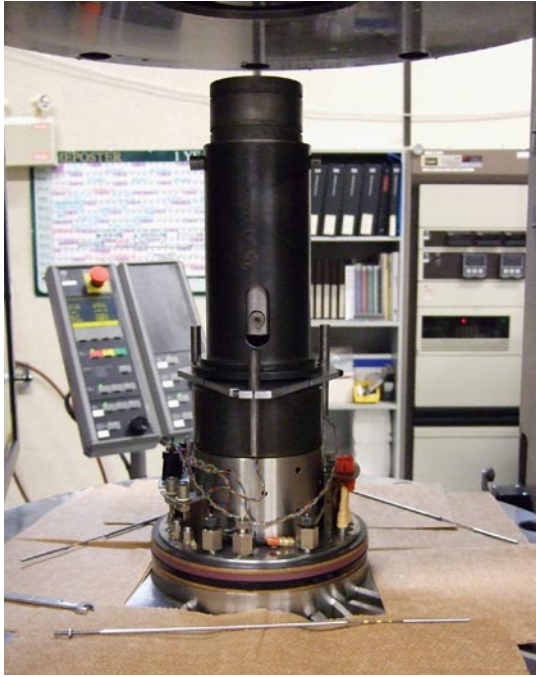
Figure 3. *Split-Grip Direct Tensile Strength Test Assembly set up in MTS Test System.*

Two Brazilian tensile test specimens were prepared from the ends of each of the tested 'dog-bone' direct tensile specimens. Direct tensile and Brazilian tensile tests were loaded in stress control to imminent failure at a rate of 0.75 MPa/s using the MTS 815 Rock Mechanics Test System /ASTM D2936 2004, ASTM D3967 2005/.

Table 1. Borehole KFM01D Specimen Selection Data.

Specimen Depth (m)	Mass (g)	Length (mm)	Diameter (mm)	Density (Mg/m³)
386.92	668.78	127.35	50.38	2.63
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387.33	670.60	127.25	50.36	2.65
387.46	671.30	127.32	50.36	2.65
387.59	671.27	127.29	50.35	2.65
387.79	670.70	127.14	50.37	2.65
387.87	671.03	127.15	50.34	2.65
388.05	671.86	127.22	50.34	2.65
388.18	672.82	127.28	50.34	2.66
388.52	673.09	127.32	50.33	2.66
388.66	672.27	127.31	50.34	2.65
388.79	672.11	127.26	50.35	2.65
388.93	672.34	127.24	50.33	2.66
399.18	670.23	127.27	50.35	2.65
399.32	671.86	127.39	50.36	2.65
399.45	670.74	127.23	50.35	2.65
399.58	671.69	127.29	50.34	2.65
399.72	671.93	127.36	50.35	2.65
399.85	672.50	127.40	50.36	2.65

Table 2. Dynamic Constants.

Specimen Depth (m)	P-wave Velocity (km/s)	S-wave Velocity (km/s)	Young's Modulus (MPa)	Shear Modulus (GPa)	Poisson's Ratio
386.92	5.09	3.18	63.00	26.71	0.18
387.05	5.13	3.18	63.70	26.81	0.19
387.19	5.05	3.15	62.09	26.28	0.18
387.33	5.01	3.13	61.25	25.99	0.18
387.46	4.97	3.08	59.61	25.04	0.19
387.59	4.97	3.09	59.95	25.28	0.19
387.79	4.93	3.04	58.41	24.50	0.19
387.87	5.05	3.15	62.06	26.26	0.18
388.05	5.01	3.10	60.72	25.54	0.19
388.18	5.05	3.17	62.64	26.63	0.18
388.52	5.13	3.17	63.59	26.65	0.19
388.66	5.13	3.18	63.84	26.87	0.19
388.79	5.17	3.23	65.35	27.68	0.18
388.93	5.21	3.26	66.63	28.27	0.18
399.18	5.05	3.15	62.04	26.25	0.18
399.32	5.02	3.08	60.08	25.07	0.20
399.45	5.17	3.18	64.08	26.79	0.20
399.58	5.13	3.18	63.78	26.85	0.19
399.72	5.09	3.18	63.37	26.86	0.18
399.85	5.06	3.17	62.62	26.62	0.18

Table 3. Specimen Dimensions.

Specimen Depth (m)	Direct Tensile (B) Diameter (mm)	Length (mm)	Brazilian (A) Diameter (mm)	Length (mm)	Brazilian (C) Diameter (mm)	Length (mm)
386.92	38.16	76.84	50.34	16.73	50.35	27.34
387.05	38.21	76.56	50.35	24.31	50.34	24.62
387.19	38.06	76.37	50.33	23.63	50.34	24.99
387.33	38.08	76.33	50.35	24.63	50.35	25.83
387.46	38.12	76.30	50.36	25.10	50.37	25.17
387.59	38.18	76.34	50.34	24.88	50.36	25.17
387.79	38.16	76.31	50.33	24.81	50.32	25.32
387.87	38.15	76.29	50.36	25.11	50.36	24.98
388.05	38.22	76.52	50.35	24.78	50.34	24.86
388.18	38.08	76.69	50.36	25.63	50.36	24.08
388.52	38.26	76.62	50.34	25.01	50.34	25.20
388.66	38.16	76.60	50.34	25.20	50.34	25.61
388.79	38.17	76.43	50.34	24.93	50.34	25.21
388.93	38.12	76.31	50.34	25.16	50.36	24.86
399.18	38.23	76.31	50.32	20.82	50.33	25.31
399.32	38.21	76.32	50.31	24.77	50.33	25.69
399.45	38.24	76.27	50.32	24.87	50.30	25.51
399.58	38.22	76.46	50.32	24.50	50.34	25.80
399.72	38.19	76.72	50.35	24.80	50.34	22.74
399.85	38.17	76.38	50.33	25.03	50.34	24.26

Test results

Twenty direct and fourty Brazilian tensile strength, σ_t, tests were conducted in this test program. The obtained results are listed in Table 4. The direct tensile strengths of the 'dogbone' specimens were calculated using the following formula:

Direct Tensile Strength $\sigma_t = P/A$ (MPa)

where

P = load at failure (N)

A = cross-sectional area at neck failure zone (mm^2)

Brazilian Tensile Strengths were calculated using the following formula:

Brazilian Tensile Strength $\sigma_t = 2P/\pi Dt$ (MPa)

where

P = load at failure (N)

D = diameter (mm)

t = thickness (mm)

Conclusions

The direct tensile test yielded lower strength values than the Brazilian test as the direct tensile test is affected to a greater degree by the presence of microfractures and microfissures in the rock. The rock fails according to the 'weakest link'. For the specimens tested in direct tension, failure occurred on a plane within the neck and perpendicular to the axis of the core. The higher Brazilian tensile strength results may be attributed to the combination of compressive and tensile stresses imposed on the rock using this test method. The compressive force must overcome the frictional forces at shearing grains or grain boundaries in order to initiate tensile failure.

Table 4. Tensile Strength Results.

Specimen Depth (m)	Direct Tensile (B)		Brazilian (A)		Brazilian (C)	
	Failure Load (N)	σ_t (MPa)	Failure Load (N)	σ_t (MPa)	Failure Load (N)	σ_t (MPa)
386.92	9,031	−7.90	25,749	−19.46	43,503	−20.12
387.05	14,840	−12.94	38,260	−19.90	40,468	−20.79
387.19	14,511	−12.76	39,136	−20.95	39,929	−20.21
387.33	13,541	−11.89	43,040	−22.09	41,665	−20.40
387.46	9,874	−8.65	40,654	−20.48	38,285	−19.22
387.59	11,645	−10.17	41,859	−21.28	36,767	−18.47
387.79	12,985	−11.35	39,946	−20.37	37,037	−18.51
387.87	15,118	−13.23	39,212	−19.74	37,846	−19.15
388.05	14,224	−12.40	35,730	−18.23	39,844	−20.27
388.18	14,317	−12.57	38,757	−19.12	34,955	−18.35
388.52	11,940	−10.39	40,426	−20.44	36,843	−18.49
388.66	14,183	−12.40	40,966	−20.56	39,044	−19.28
388.79	13,829	−12.09	38,917	−19.74	41,657	−20.90
388.93	12,286	−10.77	34,306	−17.24	39,735	−20.21
399.18	9,790	−8.53	29,298	−17.80	30,967	−15.48
399.32	13,340	−11.63	35,688	−18.23	36,068	−17.76
399.45	11,038	−9.61	34,002	−17.30	31,709	−15.73
399.58	12,623	−11.00	35,747	−18.46	37,712	−18.49
399.72	11,696	−10.21	35,208	−17.95	33,244	−18.49
399.85	12,328	−10.77	36,818	−18.61	36,135	−18.84