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Point load testing of intact rock and of samples with sealed fractures

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Abstract

Point load test (PLT) has been performed on the rock cores from the subvertical borehole KFM07C. The objective of this study is to collect additional data with this method, from the main rock type, granite to granodiorite, of the planned site for the spent nuclear fuel repository. The result show that the tensile strength (ITS) calculated from the PLT results has a mean value of 14 MPa for the whole borehole. The 77 tests have been conducted on samples in the borehole depth interval 100-500 m. The results vary to some extent along the borehole. The results from KFM07C have also been compared to previous tests in KFM24 in the same rock type, and the results are similar.

The second part of the PLT study is concerned with the strength of sealed fractures in the rock. Tests with point loading parallel with the sealed fracture planes have been performed. The 35 tested sealed fracture samples had different characteristics with respect to infilling minerals and thickness. The sealed fractures with either calcite, chlorite or laumontite as main infilling, irrespective of thickness, fail on average at about a third of the load compared to intact rock. The fractures sealed with adularia have about the same point load strength as the intact rock. The results show that the thicker sealed fractures are about half as strong as the thin sealed fractures. An additional series of test is recommended to strengthen the conclusions.

Sammanfattning

Punktlasttest (PLT) utfördes på borrkärnor från det subvertikala borrhålet KFM07C. Syftet med denna studie var att samla in ytterligare data med denna metod från huvudbergarten, granit till granodiorit, i området som planeras för slutförvaret för använt kärnbränsle. Resultaten visar att draghållfastheten (ITS) som beräknas från punktlasttesterna har ett medelvärde på 14 MPa för hela borrhålet. Testerna gjordes i borrhålsintervallet 100–500 m djup. Resultaten varierade i viss mån längs borrhålet. Resultaten från KFM07C jämförs även med tidigare provning från KFM24 i samma bergart och resultaten är liknande.

Den andra delen av PLT-studien avsåg styrkan hos läkta sprickor i berget. Provning har utförts med punklast parallellt med läkta sprickplan. De 35 provade läkta sprickorna hade olika karaktär vad gäller mineralfyllnad och tjocklek. De läkta sprickorna som hade antingen kalcit, klorit eller laumontit som det huvudsakliga mineralet, oavsett tjockleken, gick i brott vid i medeltal en tredjedel av lasten jämfört med intakt berg. Sprickorna läkta med adularia har ungefär samma punktlasthållfasthet som det intakta berget. Resultaten visar att de tjockare läkta sprickorna är ungefär hälften så starka som de tunnare sprickorna. En ytterligare provningsserie rekommenderas för att stärka slutsatserna.

Content

1 Introduction

1.1 Background

1.1.1 PLT on intact rock in Forsmark

During 2021 the point load test method (PLT) was evaluated using samples from cored borehole KFM24 (Hakami and Winell 2021). The results indicated that this method could be useful to collect large numbers of data on the intact rock strength, and that there was a correlation between PLT and laboratory test data on indirect tensile strength (ITS, “Brazilian test”) which gives a similar load situation as the PLT. To increase the database supporting the method, and to assess potential differences in strength with depth and between boreholes, additional PLT were conducted on samples of the same rock type from another borehole (KFM07C) at different depths.

1.1.2 PLT evaluation for sealed fractures

The second part of this report concerns point load tests on sealed fractures. The background to this study is that the site investigations have shown that there is a large number of sealed fractures in the bedrock in Forsmark, and that the number of sealed fractures is significantly higher than the open fractures (Table 1-1and Figure 1-1). The observed frequency of sealed fractures in the investigated boreholes varies, but the average is generally in the order of 2-3 sealed fractures per meter (difference between frequency of *all fractures* and *Open fractures* in Table 1-1). Note that the data in Table 1-1 are only from sections *outside* the defined deformation zones.

Table 1-1. Frequency statistics of fractures in cored boreholes at Forsmark outside deformation zones (Stephens et al. 2007).

Cored borehole	Total number of fractures	Open fractures	Partly open fractures	Sealed fractures	Percentage of open fractures in the borehole	Fracture frequency per metre (all fractures)	Fracture frequency per metre (Open fractures)
KFM01A	1,025	537	30	458	55%	1.24	0.65
KFM01B	764	189	15	560	27%	2.30	0.57
KFM01C	3,625	909	88	2,626	28%	23.71	5.94
KFM01D	1,231	339	24	868	29%	1.90	0.52
KFM02A	865	55	25	785	9%	1.33	0.08
KFM03A	1,453	171	77	1,205	17%	1.77	0.21
KFM03B	121	10	5	106	12%	1.70	0.14
KFM04A	2,109	449	44	1,616	23%	2.66	0.57
KFM05A	1,601	347	27	1,227	23%	2.58	0.56
KFM06A	1,599	321	42	1,236	23%	2.54	0.51
KFM06B	222	106	15	101	55%	4.14	1.97
KFM06C	2,391	559	30	1,802	25%	3.95	0.92
KFM07A	1,372	159	16	1,197	13%	2.24	0.26
KFM07B	1,174	380	39	755	36%	4.87	1.58
KFM07C	1,003	127	10	866	14%	3.35	0.42
KFM08A	2,468	327	22	2,119	14%	4.57	0.61
KFM08B	555	145	21	389	30%	3.27	0.85
KFM08C	2,208	227	22	1,959	11%	3.37	0.35
KFM09A	3,430	710	51	2,669	22%	5.55	1.15
KFM09B	1,488	265	34	1,189	20%	4.19	0.75
KFM10A	1,280	329	36	915	29%	3.98	1.02

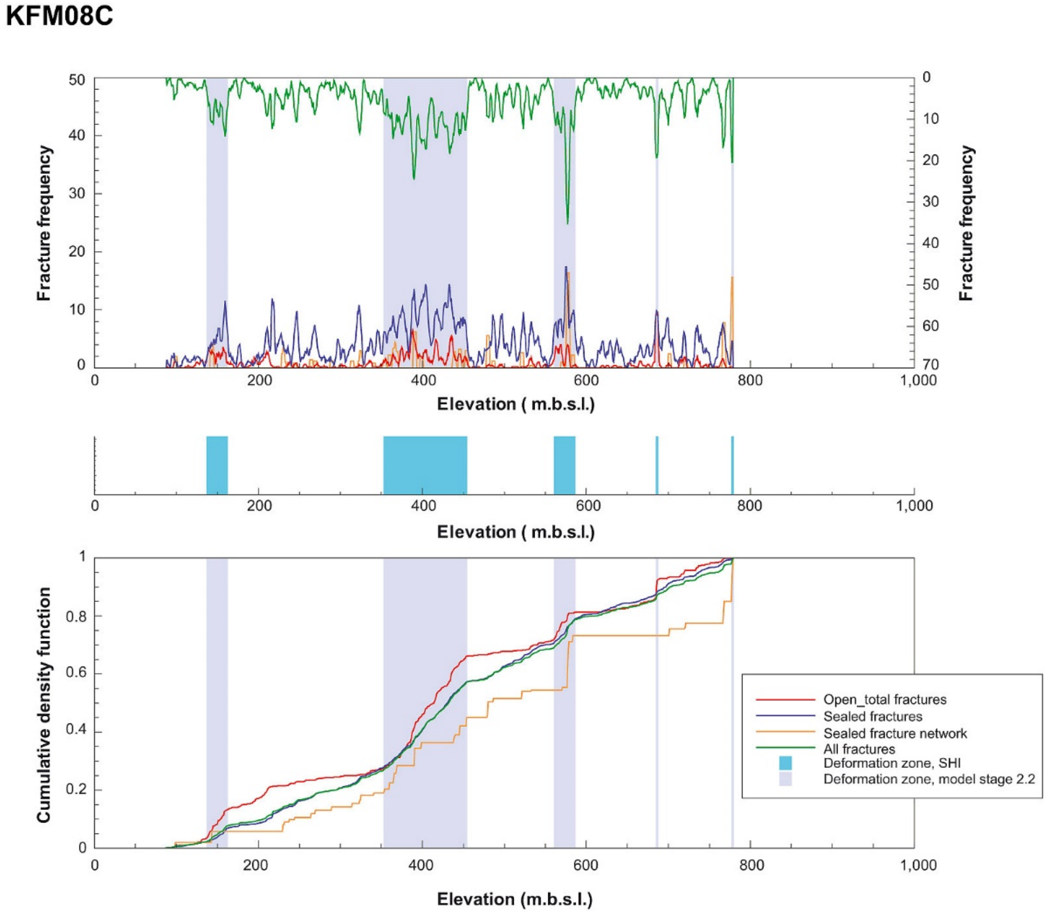

Figure 1-1. *Example of fracture frequency plot for borehole inside the planned repository site, KFM08C. The upper diagram is a moving average plot with a 5 m window and 1 m steps, and the lower diagram is a cumulative frequency plot. The deformation zones modelled during investigation stage 2.2 are marked on both plots. The sealed fractures are shown with blue line (Stephens et al. 2007)***.**

The type of mineral infilling of sealed fractures varies, and Figure 1-2 shows an example of mineral mapping result for the main fracture domain (FFM01) in which the repository is planned. The figure also presents the variation in occurrence of the different infilling minerals. These different infilling minerals, and fracture age etc., are expected to give clear differences with respect to strength. Laboratory tests of shear strength of sealed fractures have been performed on four sealed fractures (Jacobsson and Flansbjer 2006), but no tensile strength tests have been conducted. Therefore, an improved mechanical characterization of the sealed fracture component of the rock mass has been suggested in the updated strategy report of the modelling methodology for rock mechanics (Hakami et al. 2022). The point load test, in this case used to split sealed fractures, was judged to be a potential method to identify and roughly quantify the tensile strength with a limited effort.

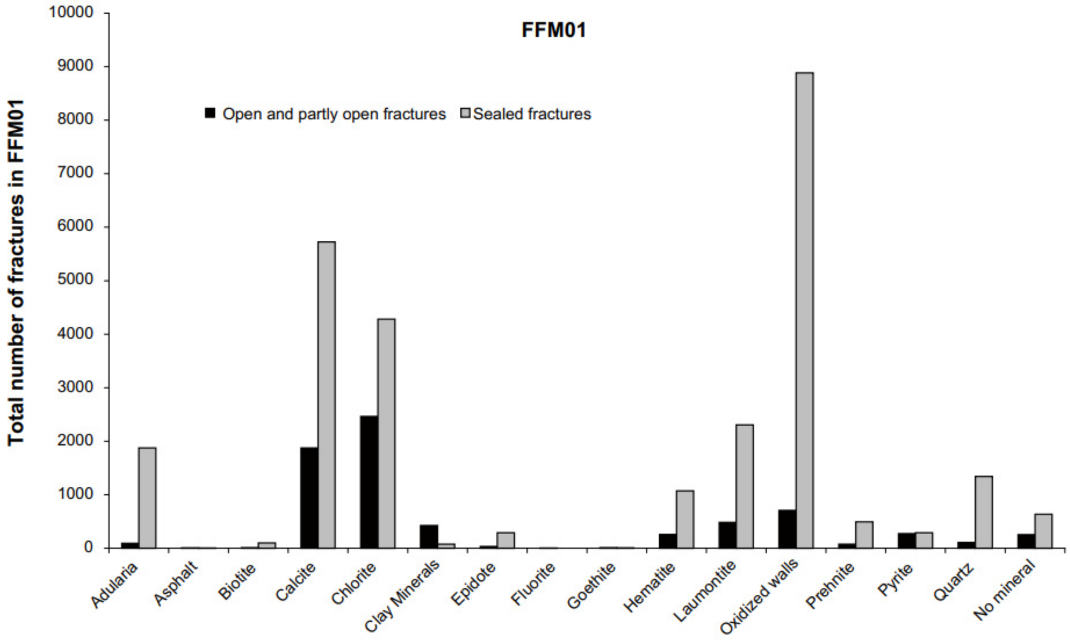

Figure 1-2. *Occurrence of fracture infilling minerals in fracture domain FFM01 (outside deformation zones). The sealed fractures are presented with grey bars. Many fractures have several infilling minerals and oxidized walls in addition (Sandström et al. 2008).*

1.2 Objective and scope

The reported activities follow the controlling documents given in Table 1-2.

The intact rock samples are from borehole KFM07C. This is an almost vertical borehole (inclination -85°) and it has been selected because rock stress measurements with overcoring have been previously performed in KFM07C, and some additional data on rock strength is of interest.

The samples for test of sealed fractures are from KFM06A, which is an inclined borehole (inclination -60°). This borehole was selected because it was assumed that the inclination of the borehole would present more fractures with a suitable angle for testing due to the general dominance of subvertical fractures in Forsmark (Stephens et al. 2007). It is known from previous studies that all fracture domains in Forsmark show a similar variation of sealed fractures with different characteristics (Sandström et al. 2008). The sampling depths in the borehole have been selected to be representative for the future deposition area, i.e., samples do not include fractures of shallow depth. The number of PLT on sealed fractures is considered to be sufficient for a first trial of the method and for the evaluation of its applicability.

Table 1-2 Controlling documents

Activity plan	**Number**	**Version**
Provning av läkta sprickors hållfasthet med punktlasttestare (PLT)	AP SFK-021-030	Version 1.0
Provning av intakt berghållfasthet med punktlasttestare (PLT)	AP SFK-021-031	1.0
Method descriptions and instruction	**Number**	**Version**
Method description for point load testing of rock	SKB MD 190.008e	1.0
Instruktion för hantering och provtagning av borrkärna (MI143.007).	SKB MI 143.007	5.0

2 Point Load testing on intact rock samples

2.1 The Point Load method

The testing procedure of intact rock in KFM07C is performed according to the method description for point load testing (SKB MD 190.008e,) and the method instruction for sampling of drill core (SKB MI 143.007).

Point load test (PLT) is an index test for the characterization of the rock material strength and may also be used for the estimation of the parameters *uniaxial compressive strength* (UCS), *uniaxial tensile strength* (UTS) and *indirect tensile strength* (ITS), also denoted *Brazilian test*.

The advantage of PLT is that the method is cost effective since the apparatus is simple and the tests are quickly to perform. The PLT can be performed both on drill cores and on irregular rock samples. Figure 2-1 shows a drill core sample mounted in the PLT apparatus for testing. The load between the conical platens are increased gradually until failure occurs and the sample breaks.

The point load strength index is expressed as the relation between the failure load and the square of the distance between the loaded points. A correction is made for the variation in size of different samples.

***Figure 2-1**. Drill core mounted for testing with Point Load Tester (PLT).*

2.2 Equipment and testing procedure for intact rock

The point load apparatus used in this study is of the brand *Matest* and has an electrical load cell with digital display, (Figure 2-2), which can measure loads within the interval 0-56 kN.

Figure 2-2. *Point load apparatus of the type Matest used in this study*

The drill core is placed between the conical platens of the apparatus, and shall have a length/diameter ratio larger than 1. The load is increased manually with a hydraulic pump until the core breaks and the maximum load is registered on the display with 2 decimals accuracy.

The tested rock type, granite to granodiorite (rock code 101057), is in general medium foliated and, therefore, all tests have been performed to avoid applying the load in the direction parallel to the foliation plane, by turning the core to get the load applied as perpendicular as possible to the foliation (the influence of loading direction with respect to foliation was a subject of study by Jacobsson (2004), and the ratio ITS_{along}/ITS_{across} was found to be 0.85). The samples are photographed both before and after the test and any observations are noted. Figure 2-3 shows the acceptability criteria for the validity of the conducted tests

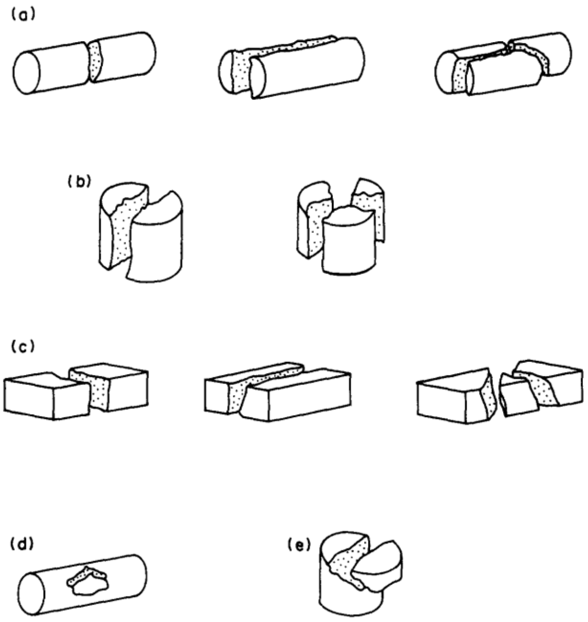

Figure 2-3. *a) Acceptable diametral tests b) acceptable axial tests c) acceptable block tests d) not acceptable diametral test e) not acceptable axial test (ISRM 1985)*

2.2.1 Parameter determination

The PLT test gives a value of the maximum load, P, which through Equation 1 gives the point load index value, I_s. To be able to compare the result of drill cores with different diameters a correction of the point load is made, corresponding to a core diameter of 50 mm, I_{s50}, (Equation 2). The core diameter of KFM07C is 50 mm, accordingly there is no need for correction between I_s and I_{s50} in this particular study.

$I_s = P/D^2$ (Equation 1)

$I_{s50} = I_s \times \surd(D/50)$ (Equation 2)

I_s = uncorrected point load (MPa)

P = applied load at failure (N)

D = core diameter (mm)

I_{s50} = corrected point load corresponding to a diameter of 50 mm (MPa).

Through Equation 3 and 4 the *uniaxial compressive strength* (UCS) and the *uniaxial tensile strength* (UTS) can be estimated.

$UCS = I_{s50} \times k$ (Equation 3)

$UTS = I_{s50} \times 1.25$ (Equation 4)

UCS = uniaxial compressive strength (MPa)
k = empirical value for the correlation factor k, based on previous measurements of UCS for similar rock types.
UTS = uniaxial tensile strength (MPa)

The multiplier 1.25 is used as a standard value for the direct tensile strength and is recommended by ISRM (1985). In this study the multiplier 1.31 will be used to estimate the ITS (indirect tensile strength) based on the results in previous study for this rock type in Forsmark (Hakami and Winell 2021). ITS is chosen in this study since it is the parameter used in the site description modelling.

2.3 Description of tested samples of intact rock

A total of 77 non-water saturated drill core samples have been taken for point load testing (PLT) from the borehole length interval 100-500 m in KFM07C. The tests have been performed with a certain angle to the foliation in the rock type. Nine tests have been rejected due to invalid breakage of the core (Figure 2-3), or breakage along a sealed fracture not noted during sampling.

All samples of KFM07C are from the main rock type in Forsmark, metagranite to granodiorite (rock code 101057). Visually, the rock is "fresh" (not weathered) for all samples with a colour ranging from greyish-red to whiteish-grey with varying intensity of both lineation and foliation. Figure 2-4 demonstrates the different appearance of the rock type. Figure 2-4a show a lineated, whiteish-grey metagranite, probably altered by albitization (from 481 m depth) and Figure 2-4b a greyish-red metagranite with no alterations and an almost massive structure (from 250 m depth).

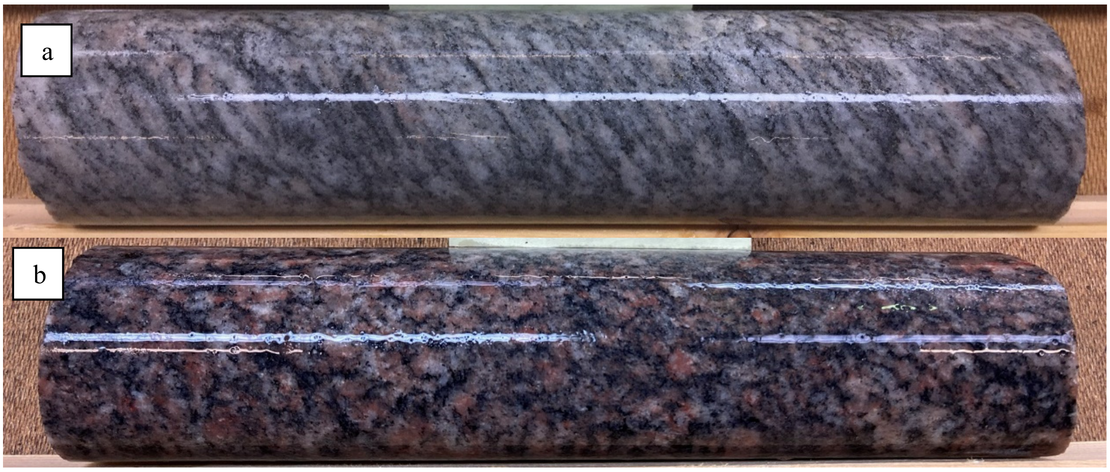

Figure 2-4. *a) Lineated whiteish-grey metagranite, probably altered by albitization b) massive, greyish-red metagranite.*

2.4 Results for intact rock

The results from the valid 69 point load tests performed on samples from KFM07C are presented in diagrams in Figure 2-5, Figure 2-6 and Appendix A. The average I_{s50} value for the *whole* borehole is 11.0 MPa, with a standard deviation of 2.0 MPa (the maximum single value measured is 15.6 MPa and the minimum is 7.0 MPa).

When divided in 100 m long intervals along the boreholes, the average varies between 10.5 MPa and 11.7 MPa (Figure 2-6).

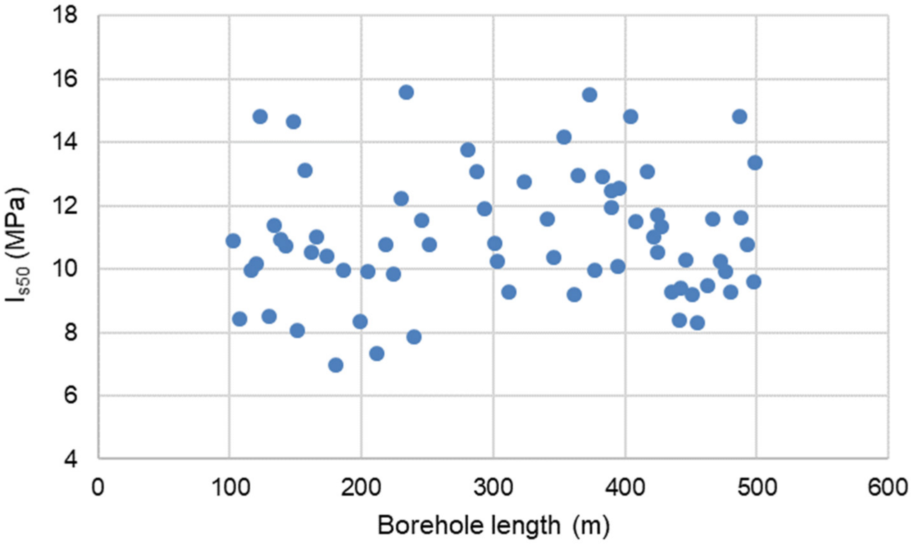

Figure 2-5. *Results from PLT tests on samples from KFM07C. All samples are taken in granite to granodiorite (101057). The borehole inclination is -85 degrees.*

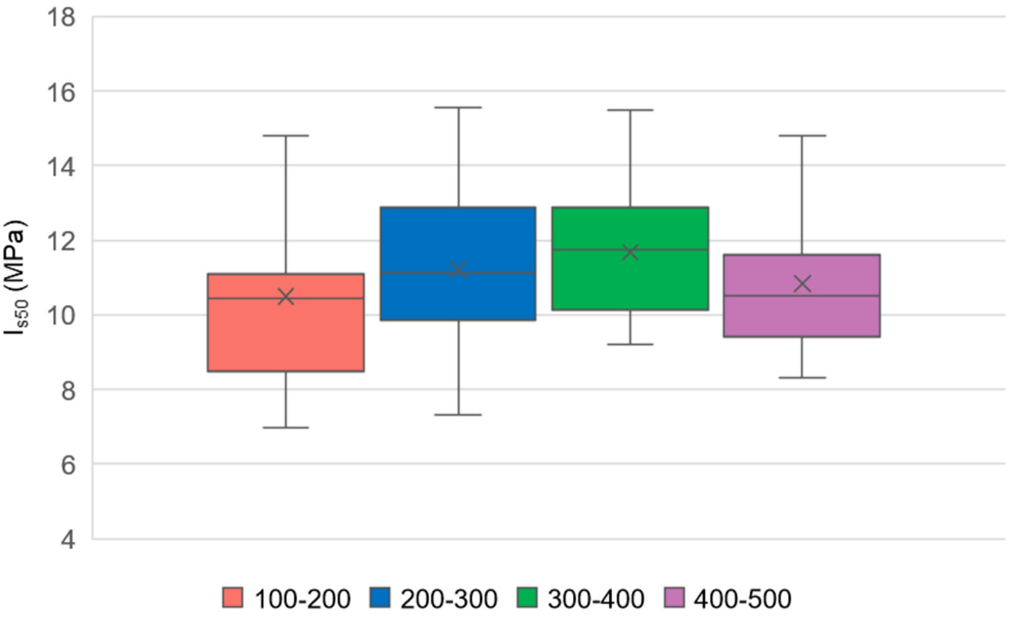

Figure 2-6. *Box plot of the same data as in Figure 2-5. The interval for each box is 100 m along the KFM07C borehole depth. The borehole inclination is -85 degrees.*

3 Point load test on samples with sealed fractures

3.1 Testing procedure for sealed fractures

A total of 35 non-water saturated drill core samples have been taken for PLT-testing from the borehole length interval 350-650 m in KFM06A. All samples correspond to the main rock type in Forsmark, metagranite to granodiorite (rock code 101057). The sampling of drill core is performed according to the method instruction (SKB MI143.007).

The method description for point load testing (SKB MD 190.008e) is intended for testing of intact rock strength and the procedure, apparatus and calculations have been described in Section 2.1 and 2.2. The testing procedure applied for the sealed fractures follow the same method description except that the conical platens are placed at the intersection of a sealed fracture surface, as shown in Figure 3-1. The load is slowly increased until breakage of the drill core along the fracture plane occurs. Still, the load situation will not be identical between the different samples where the angle of the fracture, and thus the fracture surface involved, is not the same. In this study the same calculation of I_s is performed as for intact rock and no other corrections for size or angles have been made.

For nine of the PLT-tests the breakage did not fully follow the sealed fracture plane and these samples were categorized in a separate group, “Not in plane”.

Figure 3-1. *A drill core mounted in the PLT-apparatus for testing of sealed fracture strength.*

3.2 Mineralogical description of samples

When mapping sealed fractures in Boremap (SKB core mapping program), the minerals are listed in order of decreasing amount. After the PLT-tests, when the entire fracture surface has been revealed, a new assessment of the most abundant mineral is made. The tested fractures are categorized into six groups, based on the most common mineral infilling in each fracture; adularia, calcite, chlorite, laumontite, quartz and oxidized walls only. The number of tests for each group has been limited by the number of suitable fractures in the current studied drill core section, 350-650 m borehole length in KFM06A.

Table 3-1. Sample grouping based on the most abundant mineral in the tested sealed fracture (most fractures have several infilling minerals, see details in Table 3-2).

Group Name	Most abundant mineral	Total number of PLT-samples in the group	Number of failures not in plane of sealed fracture
adu	Adularia	4	1
ca	Calcite	9	0
chl	Chlorite	13	2
lau	Laumontite	2	0
qz	Quartz	5	4
ox	Oxidized walls (only)	2	2

Figure 3-2 shows example photographs of sealed fracture surfaces after breakage with the PLT, from the different groups, in Table 3-1. Detailed geological description of fracture infilling minerals in general, and age of different generations of fractures in Forsmark can be found in Sandström et al. (2008).

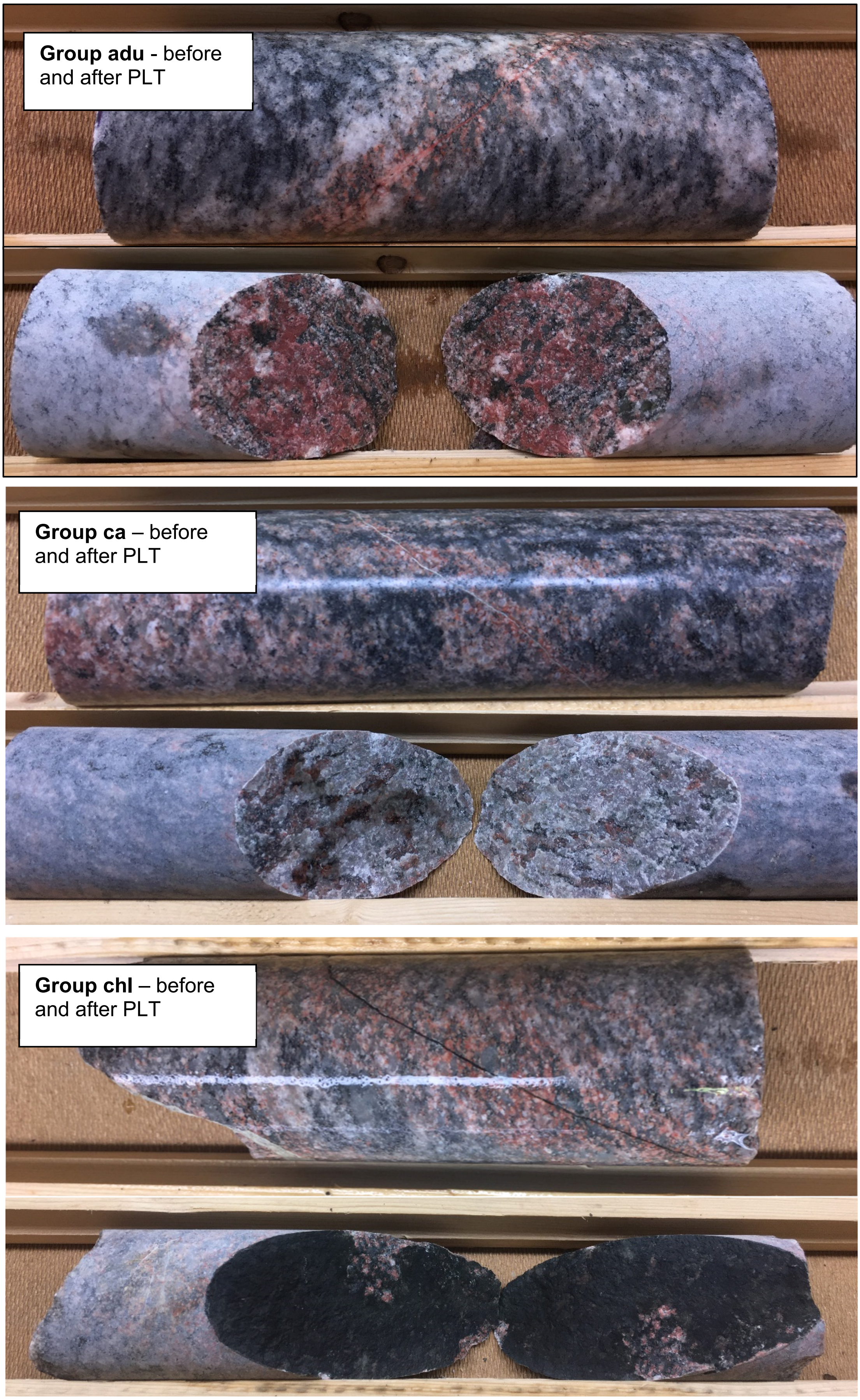

Figure 3-2*. Examples of fractures in the different groups, categorised after most abundant mineral infilling. Group adu: adularia, Group ca: calcite, Group chl: chlorite.*

Figure 3-2 continued. *Examples of fractures in the different groups, categorised after most abundant mineral infilling. Group lau: laumontite, Group ox: oxidized walls (in this case breakage not in plane), Group qz: quartz.*

Table 3-2. Sealed fracture samples from KFM06A included in the study. For definition of groups see Table 3-1 and Figure 3-2.

Group	Sample number	Sample depth, sec up (m)	Sample depth, sec lo (m)	Tested fracture depth (m)	Fracture width** (mm)	Angle against borehole axis (°)	Fracture minerals observed on sample surfaces, in order of abundance. *
adu	19	567.10	567.25	567.181	0.5	36	adu, ox walls
	20	567.65	567.82	567.728	0.5	33	adu, ox walls
	23	645.59	645.73	645.674	0.5	28	adu, qz, ox walls
	24	645.03	645.18	645.099	1	30	adu, chl, qz, ox walls
ca	29	354.13	354.28	354.183	0.5	42	ca
	30	366.00	366.2	366.112	1	55	ca
	11	448.30	448.50	448.501	0.5	39	ca, (adu, chl, ox walls)
	10	422.60	422.85	422.742	0.5	45	ca, (adu, ox walls)
	16	530.24	530.48	530.315	0.5	42	ca, chl, ox walls
	21	573.92	574.08	574.013	0.5	38	ca, lau, ox walls
	3	363.08	363.28	363.175	1	30	ca, ox walls
	8	401.00	401.20	401.129	1	42	ca, qz, chl
	2	359.15	359.35	359.224	0.5	35	ca, qz, ox walls
chl	5	380.83	381.04	380.891	0.5	53	chl, ca
	26	641.75	645.95	641.804	0.5	26	chl, ca, hem, ox walls
	1	351.41	351.65	351.576	1	25	chl, ca, ox walls
	14	523.08	523.25	523.156	0.5	32	chl, ca, ox walls
	15	526.53	526.69	526.628	1	71	chl, ca, ox walls
	37	647.08	647.27	647.175	0.5	29	chl, ca, ox walls
	35	620.44	620.64	620.536	2	27	chl, ca, qz, lau, adu, ox walls
	6	393.70	393.90	393.800	0.5	41	(chl, hem), ox walls
	36	644.60	644.82	644.743	0.5	31	chl, hem, ox walls
	34	609.13	609.33	609.214	0.5	31	chl, lau, adu, ox walls
	31	366.63	366.8	366.717	0.5	25	chl, ox walls
	9	410.70	410.90	410.780	0.5	51	chl, ox walls
	33	573.43	573.68	573.565	0.5	25	chl, qz, ca, ox walls
lau	17	543.24	543.44	543.330	0.5	36	lau, chl, ox walls
	27	622.48	622.79	622.629	1	31	lau, qz, chl, ox walls
qz	18	566.42	566.63	566.525	0.5	32	qz, chl, ox walls
	22	607.92	607.20	607.120	0.5	23	qz, chl, ox walls
	28	645.74	645.90	645.821	0.5	28	qz, chl, ox walls
	7	397.00	397.20	397.099	1	42	qz, chl, adu, ox walls
	32	509.54	509.80	509.68	0.5	21	qz, chl, ox walls
ox	4	367.92	368.10	368.013	0.5	30	ox walls
	12	481.85	482.07	481.960	0.5	38	ox walls

*adu = adularia, ca = calcite, chl = chlorite, lau = laumontite, qz = quartz, hem = hematite, ox walls = oxidized walls

** The "width" is the average thickness of fracture including the fracture infilling (as opposed to the "aperture" which is only the void). For these fully sealed fractures the width equals the thickness of the infilling. All fracture with an estimated average width <1mm is given the value 0.5 mm. Widths ≥ 1mm is estimated in the optical televiewer log image during core mapping.

3.3 Results for sealed fractures

The result from the point load tests of the sealed fractures in KFM06A are presented in Table 3-3 and Figure 3-3. The core from KFM06A has the diameter 50 mm.

Table 3-3. Result for point load tests on sealed fractures in KFM06A

Group	Sample number	Applied load (kN)	Is (MPa)	Failure not in plane of sealed fracture	Comment
adu	19	30.8	12.32		
	20	25.4	10.16		
	23	24.9	9.96		
	24	19.7	7.88	X	
Mean			***10.08***		*4 samples in group*
ca	29	6.0	2.40		
	30	2.4	0.96		
	11	16.7	6.68		
	10	7.4	2.96		
	16	6.0	2.40		
	21	11.7	4.68		
	3	11.9	4.76		
	8	6.2	2.48		
	2	10.3	4.12		
Mean			***3.49***		*9 samples in group*
chl	5	5.9	2.36		
	26	8.2	3.28		
	1	0.5	0.20		
	14	16.5	6.60		
	15	1.0	0.40		
	37	1.3	0.52		
	35	9.1	3.64		
	6	5.9	2.36		Very little chlorite and hematite
	36	14.6	5.84		
	34	9.8	3.92		
	31	1.8	0.72		
	9	38.8	15.52	X	Very little chlorite
	33	20.5	8.20	X	
Mean			***4.12***		*13 samples in group*
lau	17	14.0	5.60		Very little mineral filling
	27	2.0	0.80		
Mean			***3.20***		*2 samples in group*
ox	4	29.7	11.88	X	
	12	22.1	8.84	X	
Mean			***10.36***		*2 samples in group*
qz	18	25.2	10.08	X	
	22	21.9	8.76	X	
	28	31.3	12.52	X	Only partial split along the plane
	7	7.9	3.16		
	32	26.0	10.40	X	
Mean			***8.98***		*5 samples in group*

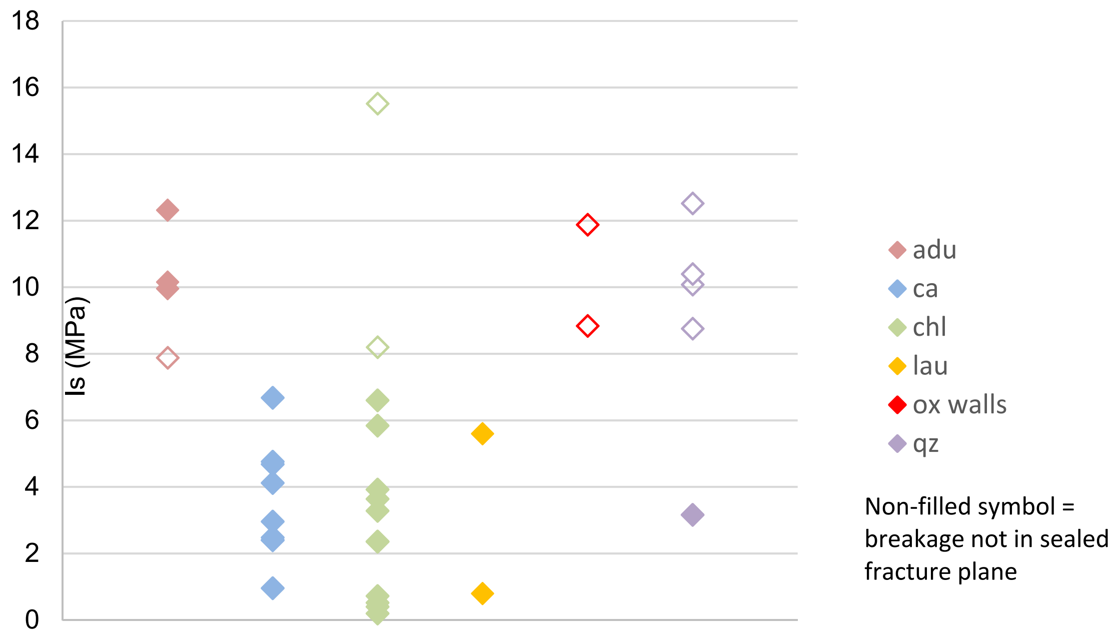

Figure 3-3. *PLT result for sealed fractures categorized into groups named after the most abundant mineral. Samples with breakage not in, or only partly in, fracture plane are marked with non-filled symbols.*

The box plot in Figure 3-4 shows the result when the sealed fracture groups with calcite, chlorite and laumontite as the main infilling minerals is merged into one category (blue box) and compared to the category with the merge of group adularia, quartz and oxidized walls (red box). The mean value for I_s in the weaker category is 3.1 MPa (blue box), and 9.6 MPa (red box) for the stronger category.

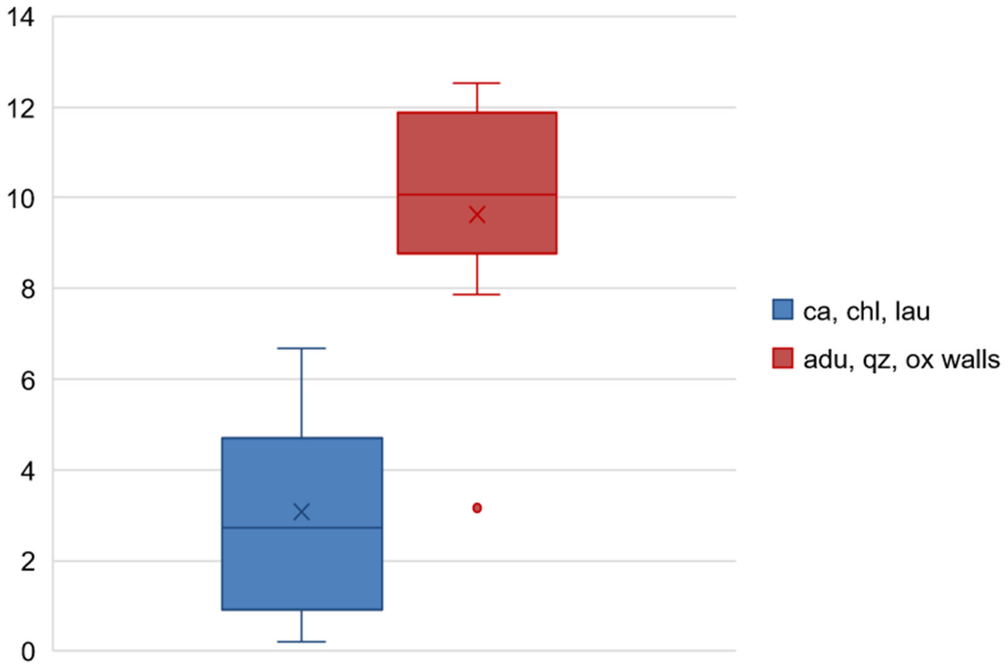

Figure 3-4. *Box plot comparison between the 22 samples with weak minerals, blue box, including group ca, chl and lau (excluding two samples in group chl where breakage was not in fracture plane) and 11 samples with stronger minerals, red box, including group adu, qz and oxidized walls (including samples with breakage not in plane). (Values further out than 1.5 times the box are considered outliers and are presented as a dot outside Min-Max span (one value in this case).*

The influence of the sealed fracture width (or thickness) on the sealed fracture strength is presented in Figure 3-5. All fractures are from the weak category in Figure 3-4 (including groups ca, chl and lau), divided in two subgroups based on if the width is ca 0.5 or 1 mm.

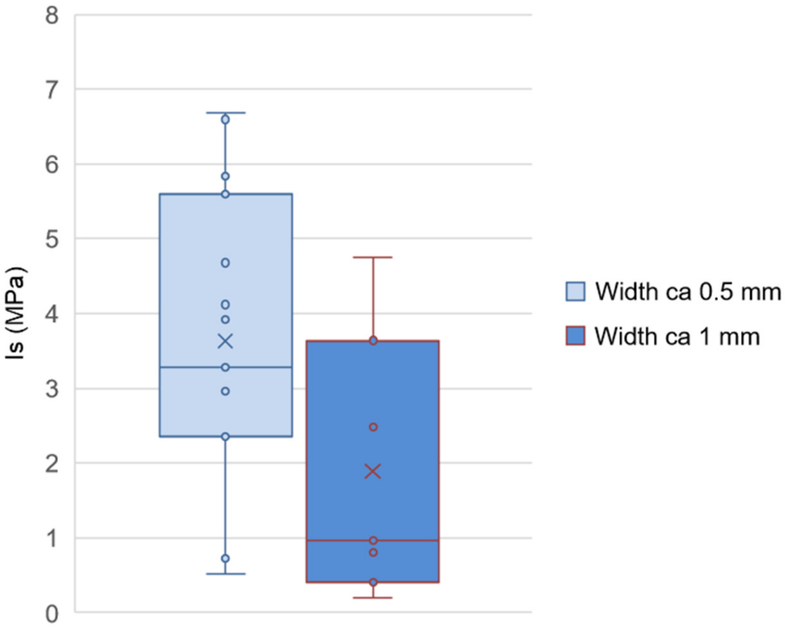

Figure 3-5. *Results for 15 samples with widths of ca 0.5 mm, light blue box, and 7 samples with widths of ca 1mm, dark blue box. Max and min values are the short end marks, inner values are marked with circles and mean value is marked with x*

Among the 11 samples with mapped dominating mineral in the stronger category there are only two samples with 1 mm thickness. These two samples correspond to the two lowest values in this category in Figure 3-4 (the dot for the outlier value at 3.2 MPa and the Min value at 7.9 MPa). It is difficult to judge if this lower strength is due to the weaker chlorite mineral that is mapped as the second most abundant mineral (i.e., occurring *together* with quartz and adularia in these samples) or if it can be attributed to the thickness itself. Nevertheless, these two samples indicate the same trend of lower strength with thicker sealed fractures as shown in Figure 3-5 for the category with weaker minerals.

4 Discussion

4.1 Result comparisons for intact rock

In Figure 4-1 a comparison is made between the result from KM07C (upper diagram) on intact rock with the PLT results from KFM24 (lower diagram), also a subvertical Forsmark borehole (Hakami and Winell 2021). All PLT-tests, in both KFM07C and KFM24, are from the same rock type, granite to granodiorite (rock code 101057). A similar variation, with mean values in the order of 9 – 11 MPa, for the I_{s50} can be observed. Both KFM07C and KFM24 seem to have some strength variation along the borehole, probably due to variation in the rock composition within the tested rock type.

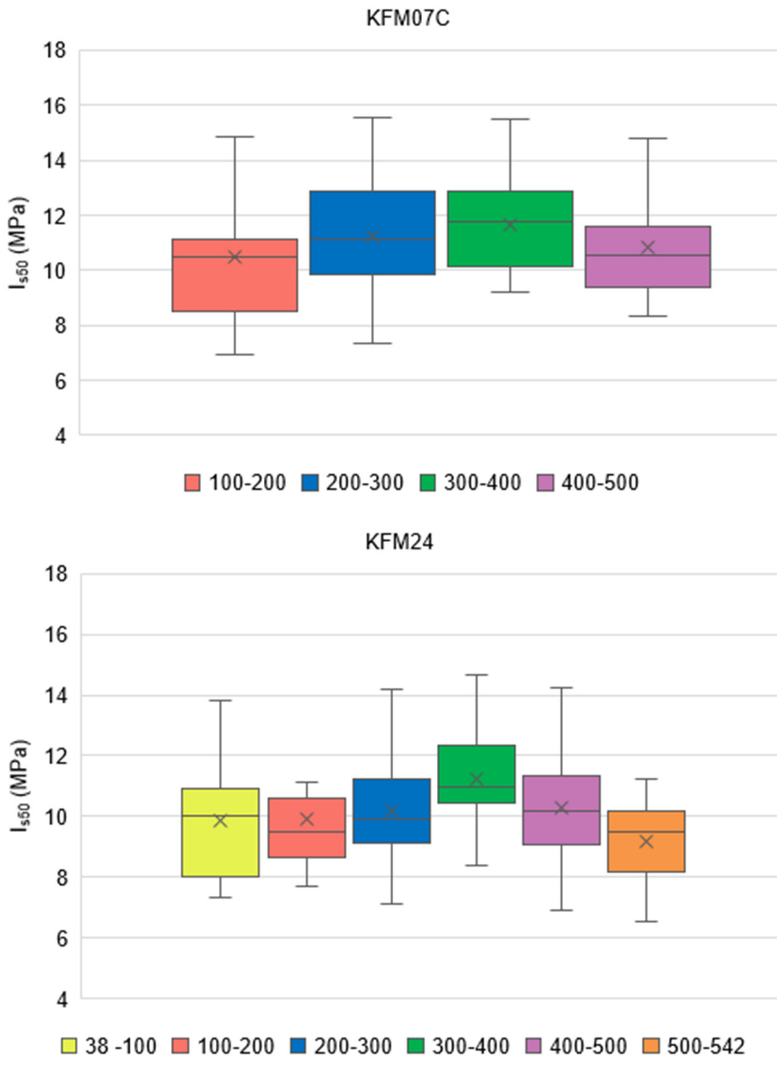

Figure 4-1. *PLT results summarized in upper diagram for borehole KFM07C as a comparison to lower diagram with previous results for KFM 24 (Hakami and Winell 2021)*__*).*__

Both boreholes indicate a lower strength for the deepest interval of the core, Figure 4-1. This could possibly be an effect of increased core damage towards depth caused by microcracking due to the stress release during the drilling operation. However, the general variation in the rock type makes such conclusion difficult to draw without further investigations.

In the study by Hakami and Winell (2021) the PLT results were compared to laboratory test results of the indirect tensile strength (ITS, "Brazilian tests") giving a linear correlation factor of 1.31. In Figure 4-2 this factor is used to predict the ITS for KFM07C from the PLT results

(I_{s50} × 1.31). The spread between single values is quite large but the 5-samples moving average varies between 12 and 16 MPa for the ITS along the borehole.

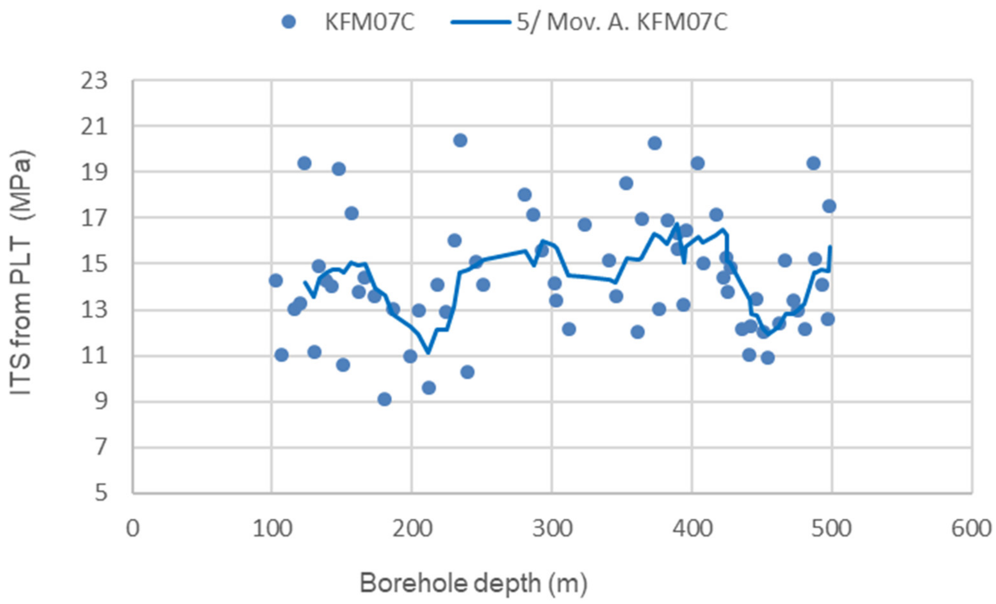

Figure 4-2. *Indirect tensile strength (ITS) derived from the PLT tests in KFM07C (I_{s50} × 1.31). The blue line is the moving average, with 5 values per average and 1m steps, for the results.*

In Figure 4-3 this moving average curve from KFM07C is compared to the same type of moving average curve for the result in KFM24. The distribution model for ITS from the site description SDM-Site (SKB 2008) in granite to granodiorite (rock code 101057), based on laboratory tests, is also marked in the diagram. The PLT results from both boreholes show a similar variation and agree quite well with the distribution model in the site description. The strength at some depth intervals in KFM07C seems to be slightly higher than expected, according to the SDM-Site model, but still within the observed span in the laboratory (the Min-Max). There are no ITS laboratory values from KFM07C available to compare with.

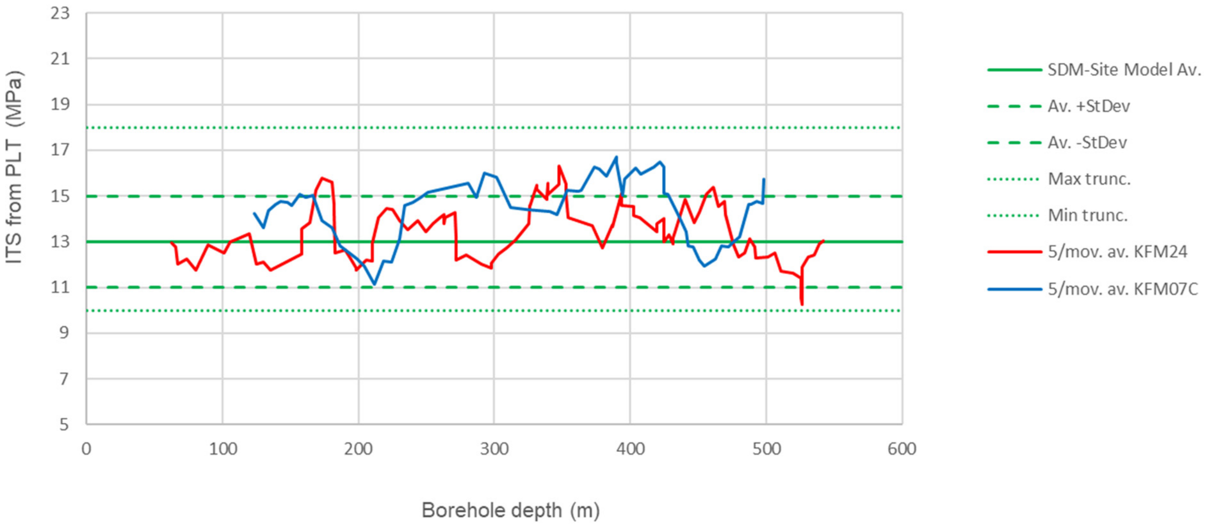

Figure 4-3. *Moving average results, with 5 values per average and 1m steps, from PLT estimates of ITS along borehole KFM07C and KFM24, respectively. The green lines show the model distribution for ITS in SDM-Site for granite to granodiorite (101057). The model is a normal distribution described by the mean standard deviation and the model truncation values.*

4.2 Result comparisons for sealed fractures

Point load tests, or laboratory tensile strength tests, on sealed fractures have not been performed previously in Forsmark. However, three samples with sealed fractures were used in laboratory *shear* tests, presented by Jacobsson and Flansbjer (2006). Figure 4-4 shows two examples. These tests indicate a shear strength for the sealed fractures clearly lower than the shear strength of the intact rock. The mineral infilling in the samples that show lower shear strength is calcite (sample 5b in figure 4-4). The shear test results qualitatively agree with the results of this study where the point load strength is clearly lower at the fracture sealed with calcite/chlorite compared to the point load strength at sealed fractures with adularia and of the intact rock.

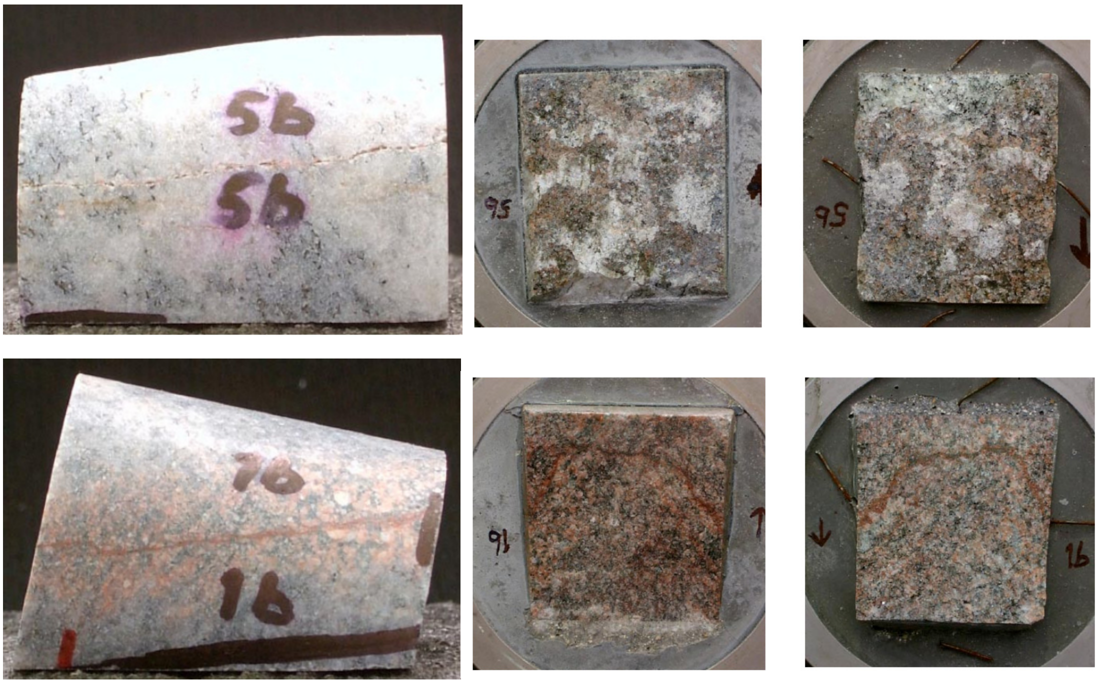

Figure 4-4. *Examples of sealed fracture samples tested in direct shear tests. Sample 5b has calcite as the main infilling mineral (to the left before shearing and to the right after shear test). The sample 1b is sealed with adularia and oxidized walls. This sample obtained a shear surface that did not follow the sealed fracture as can be seen in the photo of surfaces after shear test. Both these samples were loaded with the same normal load during shearing, 5MPa. The sample 5b had a shear strength of 10.2 MPa and sample 1b a strength of 23.5 MPa (Jacobsson and Flansbjer 2006)*

Within the campaign of *uniaxial compressive strength* (UCS) of the site investigation SDM-Site, a few samples included the so called “sealed fracture network”. This is a fairly common type of sealed networks in Forsmark and consists of thin fractures with filling of adularia and/or oxidized walls (Figure 3-3). The ordinary UCS tests performed on these samples showed strengths in the order of the intact rock strength. These results are in agreements with the finding in this report that sealed fractures with infilling of adularia and oxidized walls are much stronger than sealed fractures with many other mineral infillings.

Figure 4-5. *Example of a core sample with sealed fracture network tested for uniaxial compressive strength (Jacobsson 2007).*

5 Conclusions and recommendations

5.1 Point load testing of intact rock

The mean indirect tensile strength in KFM07C, calculated from PLT, for granite to granodiorite (rock code 101057) along the tested borehole length interval is 14 MPa, with a standard deviation of 2.6 MPa. These results with PLT in KFM07C are similar to results from KFM24 in the same rock type.

Single ITS values, calculated from PLT, have only slightly more spread than single laboratory ITS values. However, since both methods have quite large spread in single values, a mean value of several tests is recommended for characterization of tensile strength using both methods.

The time required for PLT tests is very short compared to laboratory indirect tensile strength tests. Therefore, it is recommended that the PLT method is considered for drill cores in which data on tensile strength are desired. PLT can be used to identify and model rock volumes with varying strength properties and further constitute the basis for decisions on additional laboratory investigations when needed.

It is judged that PLT could also be a useful method in the construction phase, since the method can be used directly at the drill site.

5.2 Point load testing of sealed fracture strength

Based on the comparison of point load strength results, samples with sealed fractures with the main infilling minerals calcite, chlorite or laumontite have about one third of the strength of the intact rock.

Although the applied load and the load position at breakage during the point load test for sealed fractures are not perfectly controlled, it is judged that the method still provides a useful basis to make fair tensile strength estimates.

Based on the observed difference in strength between intact rock and sealed fractures, it can be concluded that sealed fractures will constitute the main weakness planes in a rock mass with very few open fractures, as expected at repository depth in Forsmark. It is recommended that the sealed fracture frequency and the sealed fracture properties should be included as an important part of future site descriptions.

The type of mineral infilling of the sealed fractures is of main importance for the strength estimates. Sealed fractures with quartz or adularia filling (and often oxidized walls) seem to have almost the same strength as the intact rock. This means that these group of fractures might be treated as intact rock (excluded from the sealed fractures) in mechanical analyses.

The width (or thickness) of the infilling also seems to influence the strength of the fracture, but the number of performed tests of different thicknesses is not sufficient to draw any certain conclusions. The available results indicate that fractures with widths of ca 1 mm are about half as strong as the more common thinner fractures. Since most sealed fractures have several infilling minerals, and the total number of samples in this first series of tests is limited, it is not possible to quantify results for all varieties of sealed fracture characteristics (infilling minerals, mineral thicknesses, surface geometry, wall rock strength etc.). It is recommended to perform an additional series of tests to strengthen the database.

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Appendix A – PLT results from intact rock in KFM07C

The PLT results from each individual Point Load test performed in this study on samples from borehole KFM07C in Forsmark is presented I Table A-1. These results are also reported in the SKB database SICADA.

Table A-1 Results from Point Load Tests (PLT) on samples from intact rock in granite to granodiorite (101057) in KFM07C.

Sample number	Boremap ID	Sample depth. sec up	Sample depth Sec lo	Diameter (mm)	Applied load (kN)	Comment	I_{s50} (MPa)	ITS (MPa)	UCS (MPa)
1	408	103.065	103.34	50	27.2		10.89	14.3	218
2	409	107.158	107.36	50	21.1		8.44	11.1	169
3	*410*	*113.064*	*113.34*	*50*	*0.0*	*Not valid*	*0.00*	*0.0*	*0*
3b	*411*	*115.406*	*115.67*	*50*	*0.0*	*Not valid*	*0.00*	*0.0*	*0*
4	412	115.786	115.96	50	24.9		9.96	13.0	199
5	413	120.14	120.27	50	25.4		10.15	13.3	203
6	414	123.523	123.67	50	37.0		14.82	19.4	296
7	415	129.979	130.18	50	21.3		8.52	11.2	170
8	416	133.652	133.8	50	28.5		11.38	14.9	228
9	417	138.747	138.9	50	27.3		10.92	14.3	218
10	418	142.61	142.89	50	26.8		10.72	14.0	214
11	419	148.045	148.24	50	36.6		14.64	19.2	293
12	420	150.879	151.1	50	20.2		8.08	10.6	162
13	421	156.681	156.85	50	32.8		13.12	17.2	262
14	422	161.472	161.68	50	26.3		10.52	13.8	210
15	423	166.322	166.53	50	27.5		11.00	14.4	220
16	424	173.157	173.35	50	26.0		10.40	13.6	208
17	425	180.443	180.72	50	17.4		6.96	9.1	139
18	426	186.205	186.52	50	24.9		9.96	13.0	199
19	427	199.083	199.36	50	20.9		8.36	11.0	167
20	428	204.559	204.75	50	24.8		9.92	13.0	198
21	429	211.56	211.8	50	18.3		7.32	9.6	146
22	430	218.13	218.31	50	26.9		10.76	14.1	215
23	431	224.5	224.71	50	24.6		9.84	12.9	197
24	432	230.097	230.31	50	30.6		12.24	16.0	245
25	433	234.139	234.34	50	38.9		15.56	20.4	311
26	434	240.038	240.21	50	19.6		7.84	10.3	157
27	435	245.584	245.81	50	28.8		11.52	15.1	230
28	436	251.221	251.45	50	26.9		10.76	14.1	215
29	*437*	*267.546*	*267.84*	*50*		*Not valid*	*0.00*	*0.0*	*0*
30	*438*	*277.434*	*277.69*	*50*		*Not valid*	*0.00*	*0.0*	*0*
31	440	280.111	287.35	50	34.4		13.76	18.0	275
32	439	280.653	280.77	50	32.7		13.08	17.1	262
33	441	293.007	293.31	50	29.8		11.92	15.6	238
34	442	301.621	301.92	50	27.0		10.80	14.1	216
35	443	303.056	303.3	50	25.6		10.24	13.4	205
36	*444*	*303.307*	*303.53*	*50*		*Not valid*	*0.00*	*0.0*	*0*
37	*445*	*303.538*	*303.78*	*50*			*0.00*	*0.0*	*0*
38	446	312.016	312.2	50	23.2		9.28	12.2	186
39	*447*	*319.782*	*319.91*	*50*		*Not valid*	*0.00*	*0.0*	*0*
40	448	323.925	324.15	50	31.9		12.76	16.7	255
41	449	341.313	341.45	50	28.9		11.56	15.1	231
42	450	345.808	346	50	25.9		10.36	13.6	207
43	451	353.461	353.68	50	35.4		14.16	18.5	283
44	452	361.712	361.87	50	23.0		9.20	12.1	184
45	453	364.248	363.4	50	32.4		12.96	17.0	259

Sample number	Boremap ID	Sample depth. sec up	Sample depth Sec lo	Diameter (mm)	Applied load (kN)	Comment	I_{s50} (MPa)	ITS (MPa)	UCS (MPa)
46	454	373.351	373.5	50	38.7		15.48	20.3	310
47	455	377.07	377.2	50	24.9		9.96	13.0	199
48	456	382.694	382.81	50	32.3		12.92	16.9	258
49	457	389.842	389.98	50	31.2		12.48	16.3	250
50	458	390.033	390.15	50	29.9		11.96	15.7	239
51	459	394.364	394.6	50	25.2		10.08	13.2	202
52	460	395.807	395.98	50	31.4		12.56	16.5	251
53	461	404.385	404.5	50	37.0		14.80	19.4	296
54	462	407.991	408.1	50	28.7		11.48	15.0	230
55	463	417.126	417.25	50	32.7		13.08	17.1	262
56	464	421.974	422.34	50	27.5		11.00	14.4	220
57	465	425.019	425.17	50	29.2		11.68	15.3	234
58	466	425.189	425.34	50	26.3		10.52	13.8	210
59	467	427.563	427.7	50	28.3		11.32	14.8	226
60	468	435.586	435.737	50	23.2		9.28	12.2	186
61	469	441.296	441.496	50	21.0		8.40	11.0	168
62	470	442.468	442.628	50	23.5		9.40	12.3	188
63	471	446.404	446.554	50	25.7		10.28	13.5	206
64	472	450.841	451.001	50	23.0		9.20	12.1	184
65	*474*	*454.547*	*454.688*	*50*		*Not valid*	*0.00*	*0.0*	*0*
66	473	454.688	454.828	50	20.8		8.32	10.9	166
67	475	462.47	462.611	50	23.7		9.48	12.4	190
68	476	467.007	467.18	50	28.9		11.56	15.1	231
69	477	472.592	472.762	50	25.6		10.24	13.4	205
70	478	476.183	476.319	50	24.8		9.92	13.0	198
71	479	480.585	480.816	50	23.2		9.28	12.2	186
72	480	487.171	487.319	50	37.0		14.80	19.4	296
73	481	488.443	488.698	50	29.0		11.60	15.2	232
74	482	492.825	493.005	50	26.9		10.76	14.1	215
75	483	497.571	497.76	50	24.0		9.60	12.6	192
76	484	498.34	498.53	50	33.4		13.36	17.5	267