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Fracture toughness tests on rock cores from borehole KFM06A using the pseudo-compact tension (*p*CT) method

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Abstract

This report presents the results of six mode-*I* fracture toughness tests performed with 50 mm-diameter rock specimens from the Forsmark future high-level radioactive waste disposal site. The specimens were sampled from core sections obtained from the borehole KFM06A at two different borehole lengths: ~380 and ~435 m. All the samples were kept submersed in tap water for one week in order to reproduce the in situ saturation conditions. Fracture toughness was determined according with the pseudo-compact tension (*p*CT) testing methodology. The average fracture toughness value of the shallowest samples is 1.83 MPa $m^{1/2}$ while the one corresponding to the deepest location is slightly smaller (1.62 MPa $m^{1/2}$). Both values are comparable with the one obtained in a previous survey conducted on specimens sampled from surface rock blocks of the same lithology (1.72 MPa $m^{1/2}$), showing that the possible weathering effects on those previous rock block samples have no significant impact in the fracture toughness.

Sammanfattning

Rapporten presenterar resultaten av sex mätningar av brottseghet (mod-*I*) på bergprover med 50 mm diameter från det planerade området för slutförvar av använt kärnbränsle i Forsmark. Proverna togs från kärnsektioner från borrhål KFM06A vid två olika borrhålslängd: ~380 och ~435 m. Alla prover hölls nedsänkta i vatten i en vecka för att reproducera det vattenmättade förhållandet in situ. Brottsegheten bestämdes med provningsmetoden ”pseudo-kompakt drag” (*p*CT). Medelvärdet för brottseghet för nivån ~380 m är 1,83 MPa $m^{1/2}$ medan medelvärdet för ~435 m är något mindre (1,62 MPa $m^{1/2}$). Båda dessa värden är jämförbara med resultatet från en tidigare undersökning som gjordes på bergprover från block på markytan i samma litologi (1,72 MPa $m^{1/2}$), vilket visar att den möjliga effekten av vittring i de tidigare blockproverna inte har någon signifikant inverkan på brottsegheten.

Contents

1 Introduction **3**

2 Materials and methods **4**
2.1 Drill cores and sample preparation 4
2.2 *p*CT fracture toughness testing 7
2.3 Testing Equipment 7
2.3.1 Pseudo-Compact Tension (*p*CT) Bench 7
2.4 Assessment of the validity of fracture toughness test results 10
2.4.1 Compliance method criterion 10
2.4.2 Plane-strain criterion 11
2.5 Statistic treatment and data reduction 12

3 Results **13**

4 Discussion and conclusions **15**

References **16**

Appendix 1 Experimental results and photograph survey **17**

1 Introduction

This document reports the experimental results of mode-*I* fracture toughness (K_{IC}) tests performed with water-saturated specimens obtained from two drill core sections (23 and 26 cm length) taken from the borehole KFM06A. This is located within the Forsmark site investigation area. The two drill cores come from different sampling levels (borehole lengths with adjusted secup to adjusted seclow of 380.25 to 380.48 m and 434.82 to 435.08 m, respectively) and both belong to the rock type 101057 (a fine- to medium-grained metagranodiorite (to granite) with a moderately to strongly developed planar mineral fabric; SKB 2013).

The drill cores were sent to the *Rock Mechanics Laboratory* in A Coruña (Spain) where they were received on December 10, 2021. Samples were sliced and grinded the 15 of December. Then, they were measured (thickness and diameter) and submersed in tap water under room temperature conditions for seven days. This procedure is aimed at saturating samples in order to approach the in situ moisture conditions. The same day of testing (December, 22), each sample was weighted and then slotted/notched to conduct the corresponding fracture toughness test.

The main objective of this report is to determine the fracture toughness K_{IC} from drill core specimens of the rock type 101057 at depth and to compare them with the previous result obtained from specimens sampled from ground surface rock blocks of the same lithology (Delgado-Martín et al. 2021) to assess the impact of possible weathering effects. The method considered for the determination of mode-*I* fracture toughness is the *pseudo*-compact tension or *p*CT approach (Muñoz-Ibáñez et al. 2020). This method and its application for the assessment of fracture toughness in rocks have been compared with the ISRM-suggested semi-cylinder bending (SCB) method (Kuruppu et al. 2014) in the SKB report P-21-02 (Delgado-Martín et al. 2021). The information obtained provides with site-specific data useful to elaborate (or to constrain) more accurate geomechanical models and predictions. Both aspects contribute to a better characterization and understanding of the behaviour of granitic rocks in Forsmark within the context of the ongoing engineering and safety studies for the disposal of spent nuclear fuel conducted by SKB.

2 Materials and methods

2.1 Drill cores and sample preparation

Two 50 mm-diameter drill cores were transferred from Forsmark to the *Rock Mechanics Laboratory, LaMeRoc*. Figure 2-1 illustrates the two cores received before their corresponding cutting and trimming. In order to make possible the correct top/bottom orientation of the sliced samples, two parallel (blue and green) lines were marked following their axis.

Figure 2-1. *Drill cores as received: KFM06A-1 on the top and KFM06A-2 on the bottom. The cores are oriented in the pictures with their left side pointing towards the shallowest depth (Adj Secup). The relative location of the blue and green lines facilitates the orientation of the samples.*

Samples were cut from the drill cores with a 350 mm diamond saw disk (*Carat* mod. P-3500) and then trimmed with a manual drill (*Optimum* BF-16V) equipped with a lapping diamond disk to ensure the required flatness and parallelism between faces. Figure 2-2 and Figure 2-3 show a photographic sequence of the slicing of the two cores. For cutting, grinding, slotting and notching, tap water was used as refrigerating fluid.

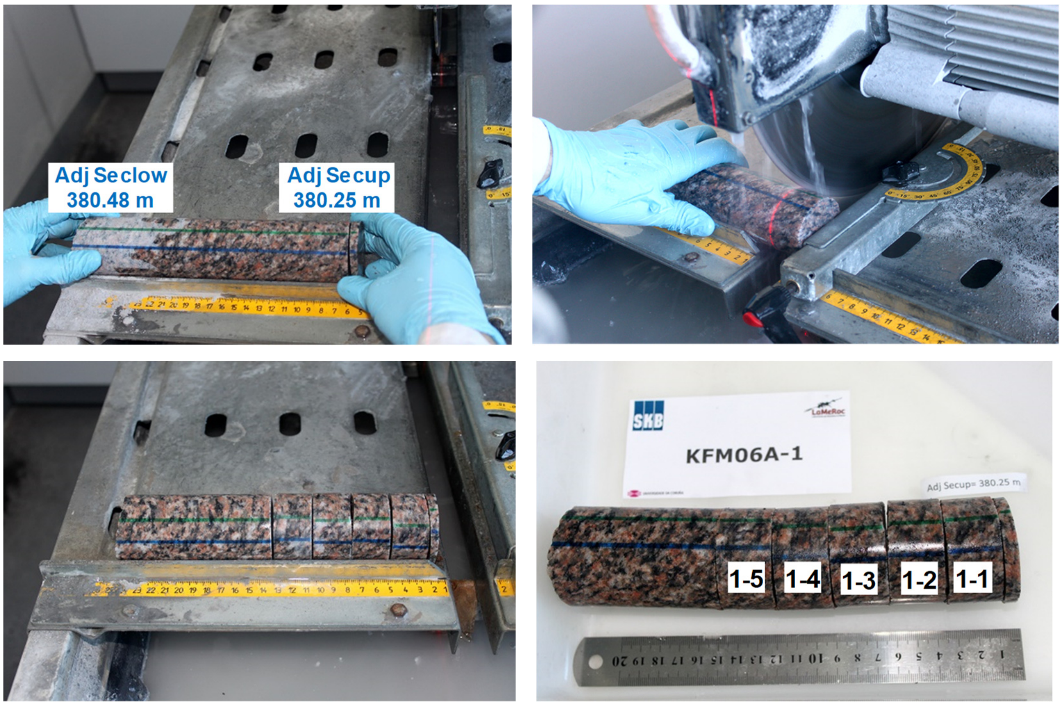

Figure 2-2. *Cutting sequence of drill core KFM06A-1 for fracture toughness sample testing.*

Figure 2-3. *Cutting sequence of drill core KFM06A-2 for fracture toughness sample testing.*

Plug dimensions (Figure 2-4) were determined with the aid of a Vernier calliper (*Mitutoyo mod. 500-197-20*; resolution = 0.01 mm). Before the determinations, the caliper was checked using a reference standard plug of 25.4 mm length and 12.7 mm diameter.

The weight of the samples was determined (before slotting and notching) with the aid of an internally calibrated digital precision scale (*Sartorius Entris 4502*; precision = 0.01g) which was further verified with a reference standard weight. The weight of the samples was measured moist, after immersion in tap water during 7 days.

No information was available about the moisture condition of the received drill cores and they were not oven-dried. Therefore, the data reported in this document related with mass and density corresponds with that of the samples in its wet condition (Figure 2-4).

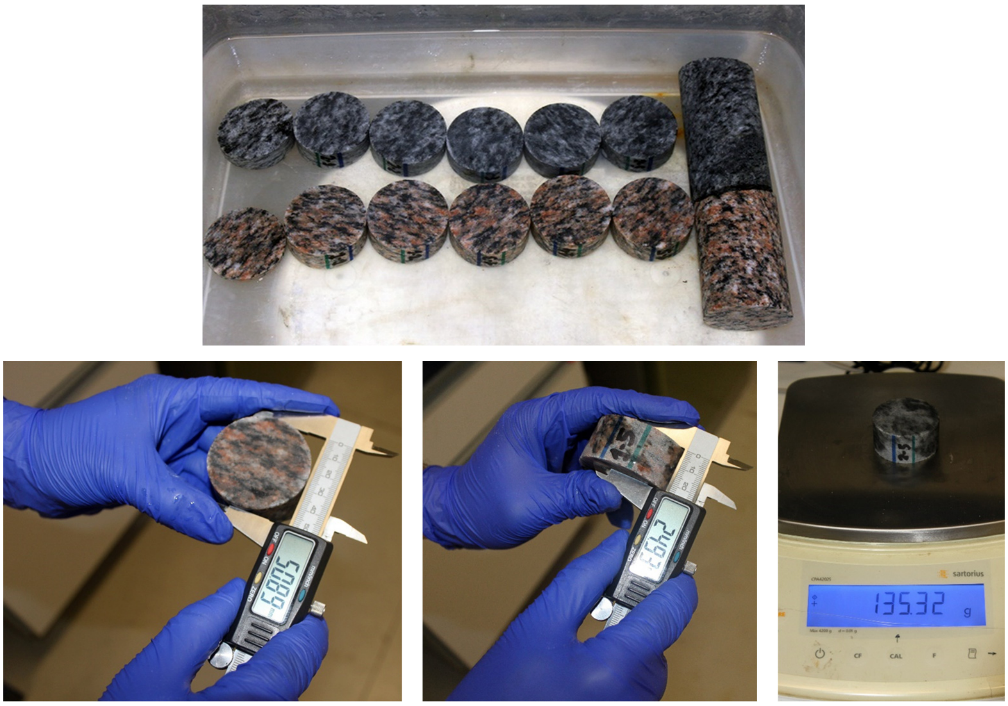

Figure 2-4. *Sliced samples immersed in tap water (top) and assessment of sample size and weight (bottom).*

Table 2-1 summarizes some relevant information related with the samples, including their location within the corresponding drill cores, average thickness and diameter or the apparent (moist) density.

Table 2-1. Representative properties of the samples prepared from drill cores KFM06A-1 and KFM06A-2.

Group	Sample	Adj Secup (m)	Adj Seclow (m)	L_{mean} (mm)	D_{mean} (mm)	L/D (–)	M (g)	ρ (kg/m³)	$ρ_{mean}$ (kg/m³)
	1-1	380.26	380.29	23.96	50.92	0.47	128.04	2624	
	1-2	380.29	380.32	23.88	50.91	0.47	128.54	2644	
KFM06A-1	1-3	380.32	380.35	25.11	50.91	0.49	135.75	2656	2645
	1-4	380.35	380.38	25.67	50.90	0.50	138.35	2648	
	1-5	380.38	380.41	24.95	50.90	0.49	134.69	2654	
	2-1	434.85	434.87	25.22	50.72	0.50	135.25	2654	
	2-2	434.88	434.90	24.12	50.75	0.48	129.29	2651	
KFM06A-2	2-3	434.91	434.93	24.12	50.71	0.48	129.31	2654	2655
	2-4	434.94	434.96	25.34	50.73	0.50	136.14	2658	
	2-5	434.97	434.99	25.22	50.71	0.50	135.32	2656	

Notes: Adj Secup = top level of the sample (borehole length); Adj Seclow = bottom level of the sample (borehole length); L_{mean} = mean thickness; D_{mean} = mean diameter; L/D = slenderness ratio; M = mass of the sample in moist condition; ρ = moist density.

Although it was decided to perform 3 tests for each received core, 5 samples were prepared in order to have a reserve in case one or two of them failed during preparation or testing. That was the case of sample 2-2 (drill core KFM06A-2), which had to be replaced by sample 2-4. The remnant drill core was preserved in case further tests were considered necessary.

2.2 *p*CT fracture toughness testing

SKB has not defined a specific protocol for fracture toughness testing. To conduct the experimental work, we have then followed general recommendations outlined by the ISRM (ISRM 1988) as well as internal laboratory procedures elaborated at the time of development of the *p*CT method (Muñoz-Ibáñez et al. 2020). Guidelines for data reporting were kept consistent with those described by SKB for other testing methods (e.g. SKB MD 190.001e ver. 4.0 and SKB 190.004e ver. 3.0, for UCS and BTS testing, respectively).

As it was described in the previous sections, the samples selected for testing were submersed during 7 days in tap water and then extracted (one every time) to cut a U-shaped groove (along the cylindrical surface of the sample; 10 mm-width and 5 mm-depth) and a centred starter notch (1 mm-width and ~11 mm-depth). The cuts, which were made just before each test, were performed with a modified tile saw equipped with a diamond disk.

2.3 Testing Equipment

According to ISRM (1988), fracture toughness investigations in rocks can be conducted with the suggested methods according to two testing levels:

- Level I (or screening level) provide fast and relatively simple access to material properties. In this level, only the maximum load (P_{max}) needs to be measured.
- Level II (or advanced level) takes into account the non-linear behavior that many rocks present. That level allows for a more detailed insight about the mechanics of the fracturing processes by continuously monitoring both the load and displacement beyond P_{max}.

Although the equipment described next can perform both levels of testing, for the present survey we only report results based on Level I testing. Reasons for that are described in following sections.

2.3.1 Pseudo-Compact Tension (*p*CT) Bench

The pseudo-compact tension (*p*CT) test (Muñoz-Ibáñez et al. 2020, Delgado-Martín et al. 2021) is based on an adaptation of the compact tension (CT) specimen described in the ASTM E399-12 (ASTM 2012) standard method for testing metallic materials and its testing principle is outlined in Figure 2-5. The two loading holes of the CT specimen are replaced by a U-shaped groove. In addition, a thin radial notch is cut to act as stress concentrator and to provide the location for crack initiation.

Once the specimen is ready for testing, carrying out the test follows a simple and straightforward procedure. The specimen is mounted on a centring cradle and put in contact with a pair of high-strength, high-stiffness steel jaws that fit into the U-shaped groove and transmit the tensile load to the sample. While one of the jaws remains in a static position, the other one is pulled apart at a constant displacement rate. The tensile load within the thin notch tends to split the specimen into two symmetrical halves. The crack initiates at the notch tip and propagates along the vertical diameter of the specimen (i.e. the ligament plane). With this basic configuration, the bottom of the sample is not affected by other loads that its own self-weight.

The testing device consists of a high-stiffness frame (AA7075-T6; E = 71.7 GPa, ν = 0.33, σ_{yield} = 503 MPa) equipped with a 50 kN push/pull load cell (*AEP Transducers mod. CTC412750KNI15*), two linear variable differential transducers (*Solartron LVDT G-series* AX/5/S), and two clip-on (COD) gages *(Epsilon Technology Co*. mod. 3541 and MTS Co. mod. 632.02).

Electric signals from all the measurement devices are integrated into a dedicated data acquisition system (*GW Instruments Inc*. instruNet 3.6). The two LVDTs, placed symmetrically on both sides on the specimen, measure the load point displacement (LPD). Simultaneously, a clip-on gage mounted on a pair of bolt-on knife edges attached to the steel jaws measures the same magnitude for redundancy. An additional COD gage can be mounted directly on the surface of the specimen to measure the crack mouth opening displacement (CMOD).

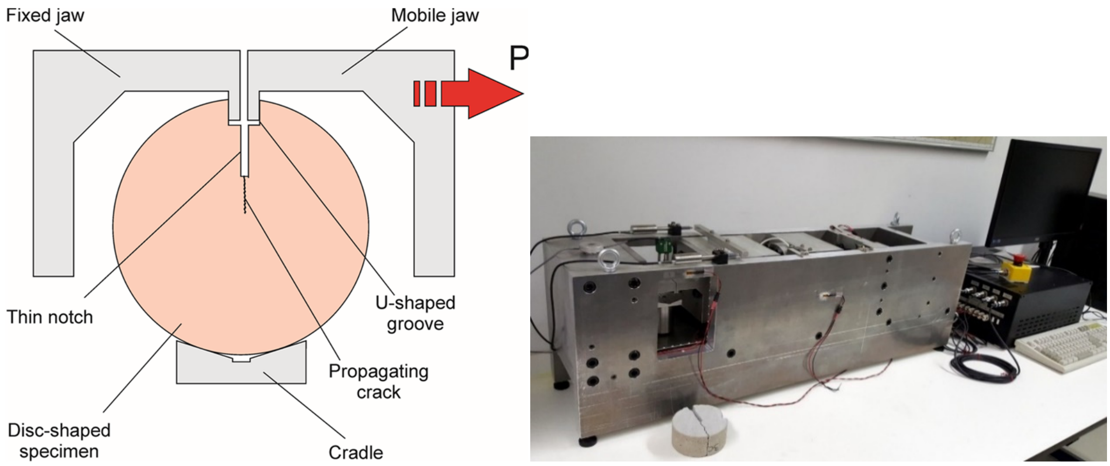

Figure 2-5. *Conceptual scheme of the pCT test (left) and frame used to conduct the experiments.*

In the *p*CT configuration CMOD can be readily compared with LPD. The movement of the steel jaw is accomplished by means of a 5-mm lead spindle (NBS mod. VFU 40005 DIN 69051 Form B), which converts the rotatory motion of an electric stepper motor (*Teco Electro Devices Co*. mod. DST56EL61A) with a step angle of 1.8° (i.e., 200 steps per revolution) into linear displacement. To improve its performance, the motor is connected to a planetary gearhead (*McLennan Servo Supp*. mod. IP-57-M2-100) with a reduction ratio of 1:100. This configuration provides a high degree of accuracy in positioning (0.018°/step), equivalent to 0.25 µm/step in terms of linear movement of the shaft, which can be maintained from 0 to 50 kN.

The control system consists of: (i) an Arduino-based microcontroller (which commands the motor with a specific program, and keeps track of the displacements and safety signals delivered by the endstops) and (ii) dedicated software (that makes it possible to set up a testing path). Control commands are transmitted in real time to the microcontroller, which executes them and returns state and displacement data.

A stainless steel bellow coupling with a clamping hub (*StS Couplings* mod. WK4/60-89-SX 49/15,) connects the motor and the spindle. A fixed-side round-type support bearing (*Hiwin* FK30-C5) provides both axial and rotational support for the spindle.

The data files obtained after each test were later filtered and post-processed in order to obtain the required properties. Post processing was performed with the aid of different *Microsoft*™ *Excel*® worksheets and plotting with the software *Grapher*® 12.7 by *Golden Software Inc*.

Characteristics of the Specimens

The *p*CT specimen is a cylindrical, disc-shaped sample that can be cut from rock cores. Its geometrical properties are summarized in Figure 2-6. This is based on the work of Muñoz-Ibáñez et al. (2020). According with their prescriptions, the *p*CT samples used should have a recommended diameter of 50 mm and a thickness to diameter (L/D) ratio of 0.5. Table 2-2 summarizes the geometric properties of the tested samples.

Table 2-2. Properties of the specimens used for *p*CT fracture toughness testing.

Group	Sample	D_{mean} (mm)	a (mm)	G_d (mm)	b (mm)	B (mm)	a/b (–)
KFM06A-1	1-1	50.92	11.10	5.00	45.92	23.96	0.24
	1-2	50.91	10.69	5.52	45.39	23.88	0.24
	1-3	50.91	10.74	5.47	45.44	25.11	0.24
KFM06A-2	2-1	50.72	10.96	4.94	45.78	25.22	0.24
	2-3	50.71	10.96	4.93	45.78	24.12	0.24
	2-4	50.73	10.74	5.15	45.58	25.34	0.24

Notes: D_{mean} = mean diameter; a = starter notch length; G_d = groove depth; b = notch length ratio; B = thickness.

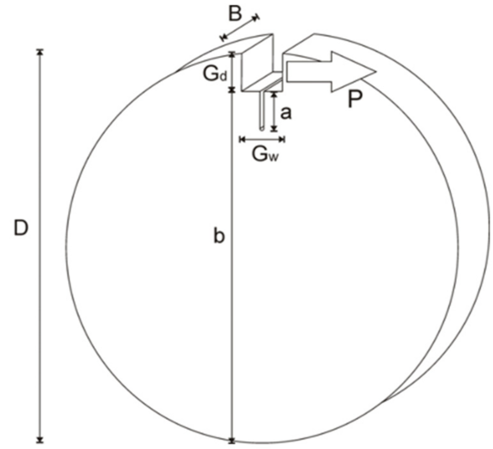

Figure 2-6. *Schematic illustration of the geometry of the pCT specimen. Notes: P = applied horizontal load; D = specimen diameter; B = specimen thickness; a = starter notch length; G_d = groove depth; G_w = groove width; b = distance from the base of the groove to the bottom of the specimen.*

Testing Procedures

*p*CT tests were executed according to the guidelines indicated by Muñoz-Ibáñez et al. (2020) and these are summarized in Table 2-3. For fracture toughness investigations in rocks, the two aforementioned testing levels, Level I (or screening level) and Level II (or advance level), are commonly reported in the literature (ISRM 1988).

Although the features and characteristics of the testing equipment are compatible with Level II, the interpretation of tests will be made based on Level I according with the considerations presented in section 2.4.

Table 2-3. *p*CT testing procedure.

Step	Description
1	Digital photographs of the specimen are taken before test execution.
2	The specimen is placed on the positioning cradle and then lifted until the steel jaws fit into the groove. The height of the cradle is manually controlled using a positioning spindle.
3	The verticality of the specimen is checked using a self-levelling cross-line laser.
4	The stress (load) and LPD (linear displacement sensor) measurement channels are zeroed in the data acquisition software.
5	The beginning of the test is concurrent to recording. Recorded data includes load and load point displacement (LPD). When the loading force starts to rise the support cradle is lowered to ensure an unconstrained behavior in the specimen. The test is executed in displacement-control mode at a constant rate of 0.1 mm/min (0.0017 mm/s).
6	The test is stopped manually (switch off) after peak load has been observed and the applied force has drop to a level close to the starting one.
7	Digital photos are taken of the specimen upon completion of each test.
8	The testing device is disassembled and carefully cleaned for the next test.

Data Processing

Following Muñoz-Ibáñez at al. (2020), the computation of KIC (in MPa m1/2) for the *p*CT testing method can be performed according to the following equation:

$$K_{IC}^{pCT} = Y'_{pCT}\sigma_{max}\sqrt{\pi a}$$

where σ_{max} is the applied stress at the critical load ($\sigma_{max} = P_{max}/(bB)$; in MPa) and B the thickness of the specimen (in m). In order to compute the specific non-dimensional stress intensity factor Y'_{pCT}, these authors provide the following equation:

$$Y'_{pCT} = C_0 + C_1\left(\frac{a}{b}\right) + C_2\left(\frac{a}{b}\right)^2 + C_3\left(\frac{a}{b}\right)^3 + C_4\left(\frac{a}{b}\right)^4$$

The coefficients C_i (i = 0 to 4) to compute the stress intensity factor are given in Table 2-4.

Table 2-4. Coefficients for the computation of the specific non-dimensional stress intensity factor Y'_{pCT} of the *p*CT fracture toughness testing method.

D (mm)	C_0	C_1	C_2	C_3	C_4
38	10.278	-24.069	82.329	-136.670	127.890
50	12.651	-47.054	158.720	-247.170	185.220
100	15.341	-74.551	260.030	-404.520	273.190

2.4 Assessment of the validity of fracture toughness test results

The assessment of the validity of fracture toughness results based on Level I testing requires the fulfilment of some acceptability criteria whose application have not been yet sufficiently discussed in rocks. In order to establish the minimum criteria for the acceptability of the test results, we have considered two complementary approaches: the application of the *compliance (or 5% secant)* method (which is covered, among others, by the standard ASTM E399-12 (ASTM 2012)) and the plane-strain criterion check.

The secant compliance method seeks to verify the applicability of the linear elastic fracture mechanics (or LEFM) postulates. A 5% secant line with a slope equal to 95% of the initial elastic loading slope is normally used to determine P_5 or P_Q.

This slope would correspond approximately with the load required to generate a ~2% (or less) apparent crack extension in the type of materials covered by the reference standards.

2.4.1 Compliance method criterion

Figure 2-7 illustrates the application of the compliance method to check the applicability of the linearity condition supporting the computation of K_{IC} based on Level I fracture toughness testing. The plot corresponds to sample 1-3 of drill core KFM06A-1. The procedure for its application is as follows:

- A linear best fit line is computed to the linear loading segment of the experimental P-CMOD curve to determine the initial compliance (Θ). This is given by the reciprocal of the slope of line AB.
- A second line, AB', is drawn with a compliance 5% greater than that of line AB.

The experimental data provides with a P_{max} value (maximum load that the specimen was able to sustain during the test) and the intersection of line AB' with the experimental curve identify the so-called conditional load or P_Q. Based on these references it is possible to compute a P_{max}/P_Q ratio that, if smaller than 1.10, supports the applicability of the LEFM hypotheses. In the case that it was larger, then an elastoplastic approach (Level II) would be required to characterize K_{IC} as a material property. In the case of the example illustrated the P_{max}/P_Q ratio is 1.01 what makes possible the computation of K_{IC} associated with Level I fracture toughness testing.

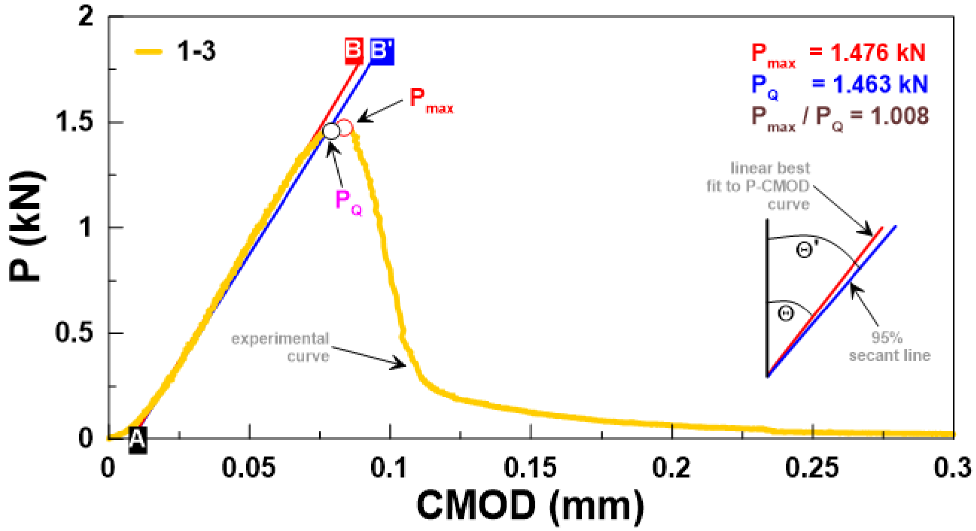

Figure 2-7. *Experimental results corresponding a pCT test used to verify the linearity criterion of the compliance method. See text for explanation. Notes: P = applied horizontal load;* P_{max} *= maximum load;* P_Q *= conditional load; CMOD = crack mouth opening displacement (≡ load point displacement in the pCT test); Θ = compliance angle; Θ' = compliance angle of the 95% P-CMOD slope.*

The ASTM E399 standard also identifies situations in which P_{max} is located between the curves AB and AB' curves and when it lays ahead of the AB' line. In the first case, the computation of K_{IC} can be directly performed based on the P_{max} value while in the second, the prescribed value to use is P_Q. Based on that, what we obtain in each case is a conditional value K_Q (that is derived from P_Q) or the true mode-I fracture toughness K_{IC} (when using P_{max}).

2.4.2 Plane-strain criterion

The ASTM E399 standard pays also attention to the fulfilment of plane-strain conditions to determine a K_{IC} value amenable of consideration of a true material property. To this respect, sample thickness is a key property as it affects how the plastic domain around the crack tip (or fracture process zone, FPZ) is fully developed within the body of the specimen (i.e. its outer boundaries are not strained) or if it interacts with them. As a rule of thumb the minimum diameter (D) of the tested sample should keep in line with the following relationship:

$$D \geq 2(K_{IC}/T)^2$$

where T represents tensile strength. This expression is derived from theoretical considerations on the size of the fracture process zone (L_{FPZ}), which is considered to be proportional to the square ratio of K_{IC} and T:

$$L_{FPZ} \propto (K_{IC}/T)^2$$

The application of the plane strain criterion is not straightforward because, although we may have an estimation of T, the computation of K_{IC} requires the testing of specific specimens. However, due to the impracticability of conducting a specific survey addressing the thickness-dependence of K_{IC} in the particular rock tested, we have considered an indirect approach based on the assessment of the L_{FPZ}. This involves the geometrical properties of the samples, the K_{IC} values computed after their testing and the estimated value of T, which in this study is assumed to correspond to that of the rock type 101057. Thus, the size of the computed L_{FPZ} can be compared with the thickness of the sample and the ligament length (distance b-a in figure 6); this way, if the L_{FPZ} results to be larger than these two properties, then the plane strain condition is challenged and the KIC value would be inaccurate.

Different researchers have considered diverse approaches to compute L_{FPZ} (e.g. Dutler et al. 2018 and references therein). Worth mentioning among them are the basic model of Irwin ($L_{FPZ,I}$), the strip-yield uniform traction model ($L_{FPZ,SU}$) and the strip-yield linear traction model ($L_{FPZ,ST}$). The corresponding expressions are given as follows:

$$L_{FPZ,I} = \frac{1}{\pi}\left(\frac{K_{IC}}{T}\right)^2 \qquad L_{FPZ,SU} = \frac{\pi}{8}\left(\frac{K_{IC}}{T}\right)^2 \qquad L_{FPZ,ST} = \frac{9\pi}{32}\left(\frac{K_{IC}}{T}\right)^2$$

2.5 Statistic treatment and data reduction

Due to the small number of tests performed (2 groups of specimens with 3 samples each), it is not possible to perform any accurate statistical assessment and the results will only be presented in terms of their mean and the corresponding standard error.

3 Results

The results are presented, first, by assessing their acceptability based on the two criterions defined above, to then, describing the specific fracture toughness values. Figure 3-1 represents the experimental curves obtained from the six samples of the two drill core specimens investigated, while each specific experiment is documented in the Appendix 1.

It was indicated previously that, in the absence of specific recommendations to assess the acceptability of fracture toughness test results in rocks, we have defined a procedure to conduct a two-step check based on the plane strain (estimated length of the fracture process zone L_{FPZ}) and the compliance (5% secant line slope method) criteria.

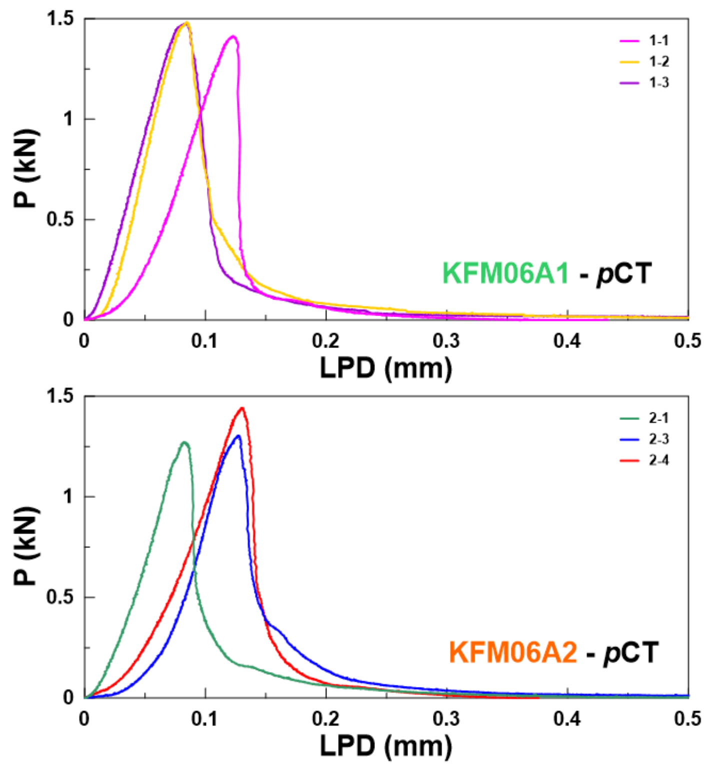

Figure 3-1. *Load vs. load point displacement (LPD) curves associated with the six pCT fracture toughness tests performed with samples from specimen KFM06A-1 (top) and KFM06A-2 (bottom).*

Table 3-1 shows the assessment of the length of the fracture process zone in the tested samples according to three different models. We see that, when considering the samples, both thickness and ligament length (b-a; see Figure 2-6) are significantly larger than the computed L_{FPZ}, indicating that the samples satisfy the plane-strain constrain.

Table 3-1. Assessment of the length of the fracture process zone according to the Irwin's ($L_{FPZ,I}$), strip-yield uniform traction ($L_{FPZ,SU}$) and the strip-yield linear traction ($L_{FPZ,ST}$) models.

Group	Sample	$L_{FPZ,I}$ (mm)	$L_{FPZ,SU}$ (mm)	$L_{FPZ,ST}$ (mm)
KFM06A-1	1-1	5.42	6.68	15.03
	1-2	5.49	6.77	15.23
	1-3	5.31	6.56	14.75
KFM06A-2	2-1	3.80	4.69	10.56
	2-3	4.05	5.00	11.25
	2-4	4.90	6.05	13.60

Table 3-2 shows the results of the assessment of the P_{max}/P_Q ratio for all the tested samples and methods. Graphical representation is also provided in the Appendix 1. We see that this ratio is clearly below the 1.10 threshold value what would confirm the applicability of LEFM formulations for the computation of K_{IC} in Level I testing. Moreover, since P_Q lays in the experimental curves slightly before than P_{max}, the conditional load must be considered to compute the conditional fracture toughness, K_Q.

On the other hand, the closeness of P_Q to P_{max} determines that the numerical values of K_Q (computed with P_Q) and K_{IC} (computed with P_{max}) are virtually the same, which makes possible to conclude that $K_Q \sim K_{IC}$. Consequently, the fracture toughness of the rock specimen KFM06A-1 is 1.83 ± 0.01 MPa $m^{1/2}$ and that of the rock specimen KFM06A-2 is 1.62 ± 0.06 MPa $m^{1/2}$.

Table 3-2. Results of the fracture toughness tests.

Group	Sample	P_{max} (N)	P_Q (N)	P_{max}/P_Q (–)	K_Q (MPa $m^{1/2}$)	$K_{Q,mean}$ (MPa m1/2)	SEM (MPa $m^{1/2}$)
KFM06A-1	1-1	1414.6	1404.6	1.01	1.83	1.83	0.01
	1-2	1484.2	1415.6	1.05	1.85		
	1-3	1475.5	1463.3	1.01	1.82		
KFM06A-2	2-1	1271.7	1242.1	1.02	1.54	1.62	0.06
	2-3	1304.8	1225.9	1.06	1.59		
	2-4	1442.4	1422.3	1.01	1.74		

Notes: Notes: P_{max} = peak load at failure; P_Q = conditional load level; K_Q = conditional fracture toughness; $K_{Q,mean}$ = mean conditional fracture toughness; SEM = standard error of the mean.

4 Discussion and conclusions

The *p*CT experimental data show that the two complementary acceptability criteria defined for the applicability of LEFM are fulfilled. Furthermore, the small difference observed between P_Q and P_{max} allows to conclude that the conditional fracture toughness (K_Q) has virtually the same value than the intrinsic fracture toughness (K_{IC}).

The experimental data is also internally consistent (i.e., low spread among sample groups) and the corresponding KIC reference values for rock specimens KFM06A-1 and KFM06A-2 are 1.83 ± 0.01 MPa $m^{1/2}$ and 1.62 ± 0.06 MPa $m^{1/2}$, respectively. These values are of the same order of the ones obtained for surface rock blocks of the same lithology from the Forsmark test site (1.72 ± 0.07 MPa $m^{1/2}$; Delgado-Martín et al. 2021), showing that the impact of possible weathering effects on the specimens sampled from surface rock blocks can be considered negligible.

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Appendix 1 Experimental results and photograph survey

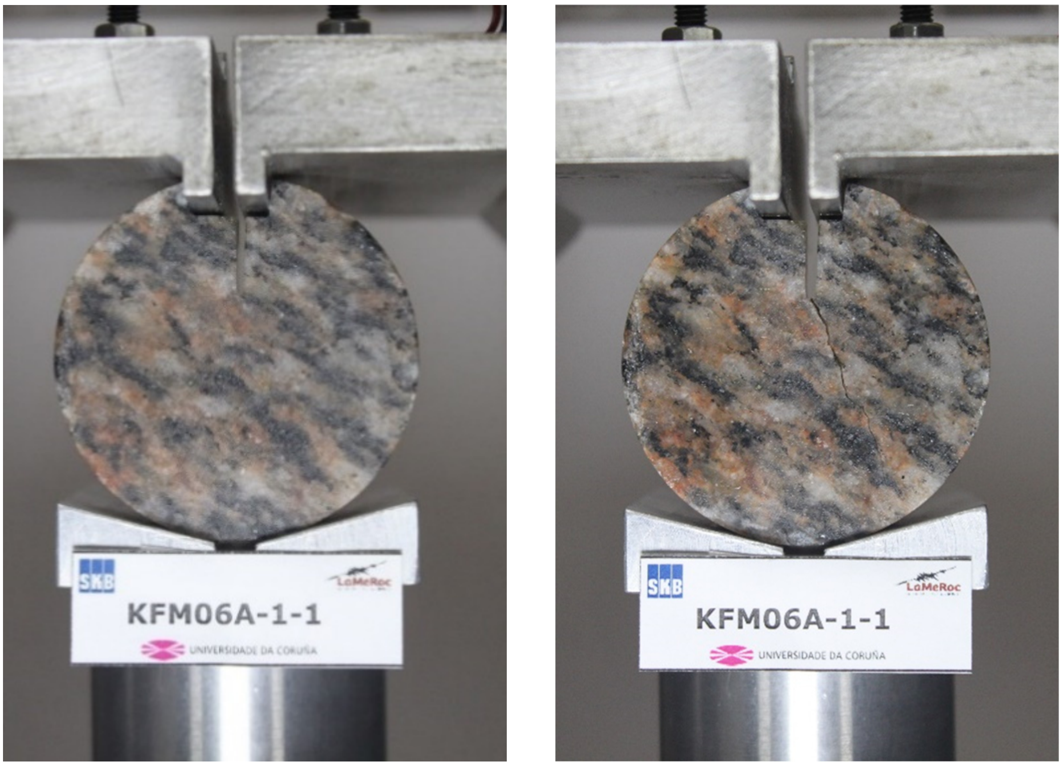

Figure A-0-1. *Sample KFM06A-1-1 before (left) and after (middle right) conducting a pCT test. The K_{IC} value obtained was of 1.38 MPa $m^{1/2}$ obtained for a maximum load of 1.42 kN.*

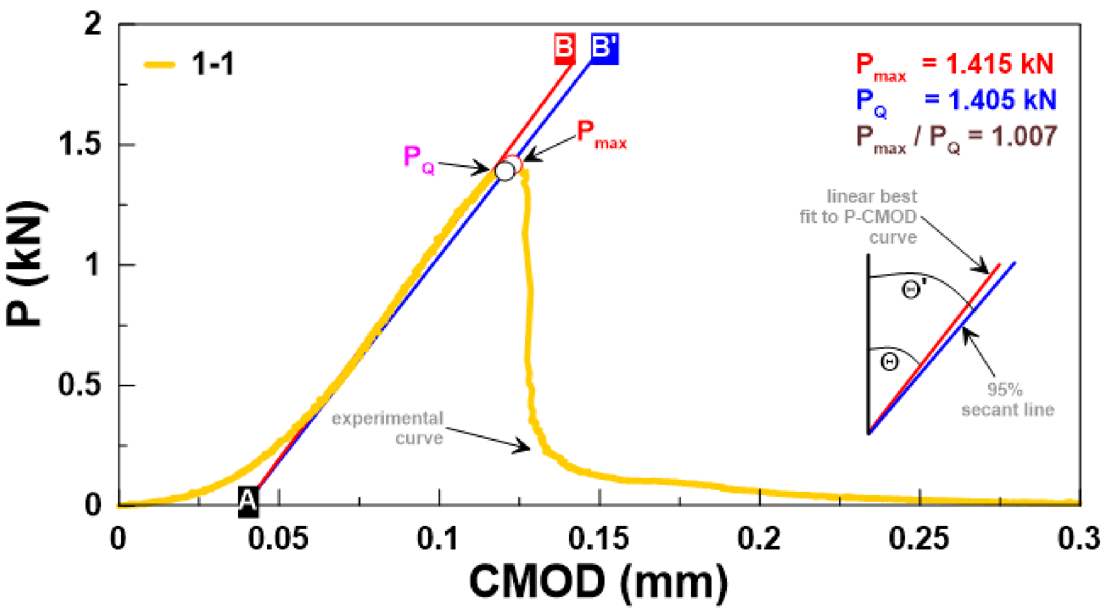

Figure A-0-2. *Experimental results of the pCT test performed with specimen 1-1 and verification of the linearity criterion of the compliance method. See text for explanation Notes: P = applied horizontal load; P_{max} = maximum load; P_Q = conditional load; CMOD = crack mouth opening displacement (≡ load point displacement).*

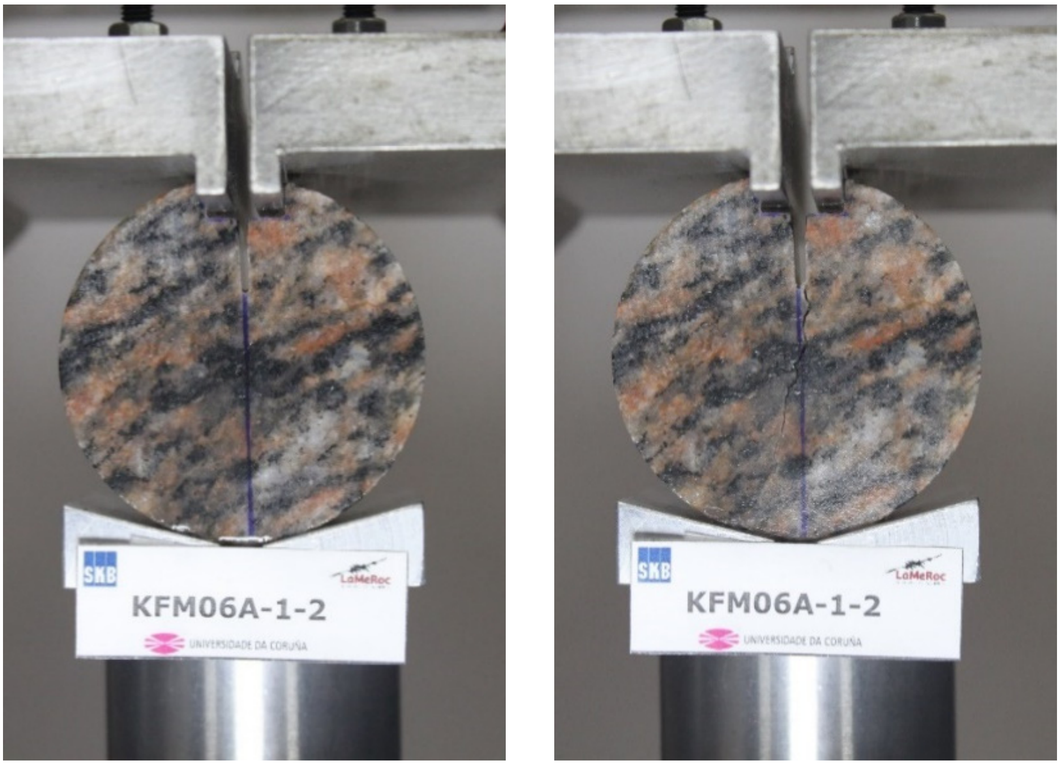

Figure A-0-3. *Sample KFM06A-1-2 before (left) and after (middle right) conducting a pCT test. The K_{IC} value obtained was of 1.87 MPa $m^{1/2}$ obtained for a maximum load of 1.48 kN.*

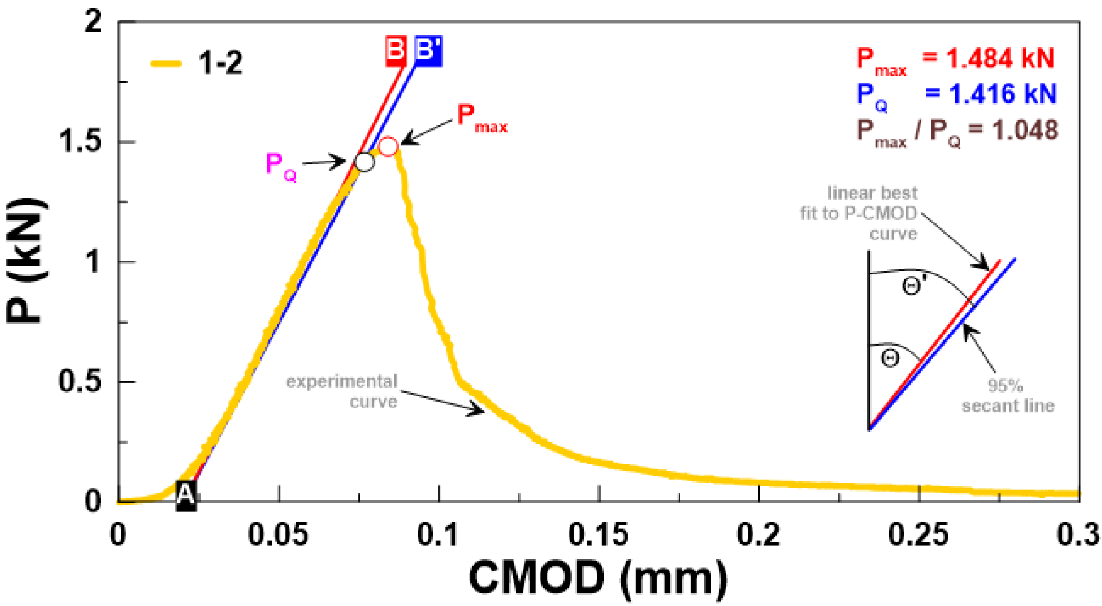

Figure A-0-4. *Experimental results of the pCT test performed with specimen 1-2 and verification of the linearity criterion of the compliance method. See text for explanation Notes: P = applied horizontal load; P_{max} = maximum load; P_Q = conditional load; CMOD = crack mouth opening displacement (≡ load point displacement).*

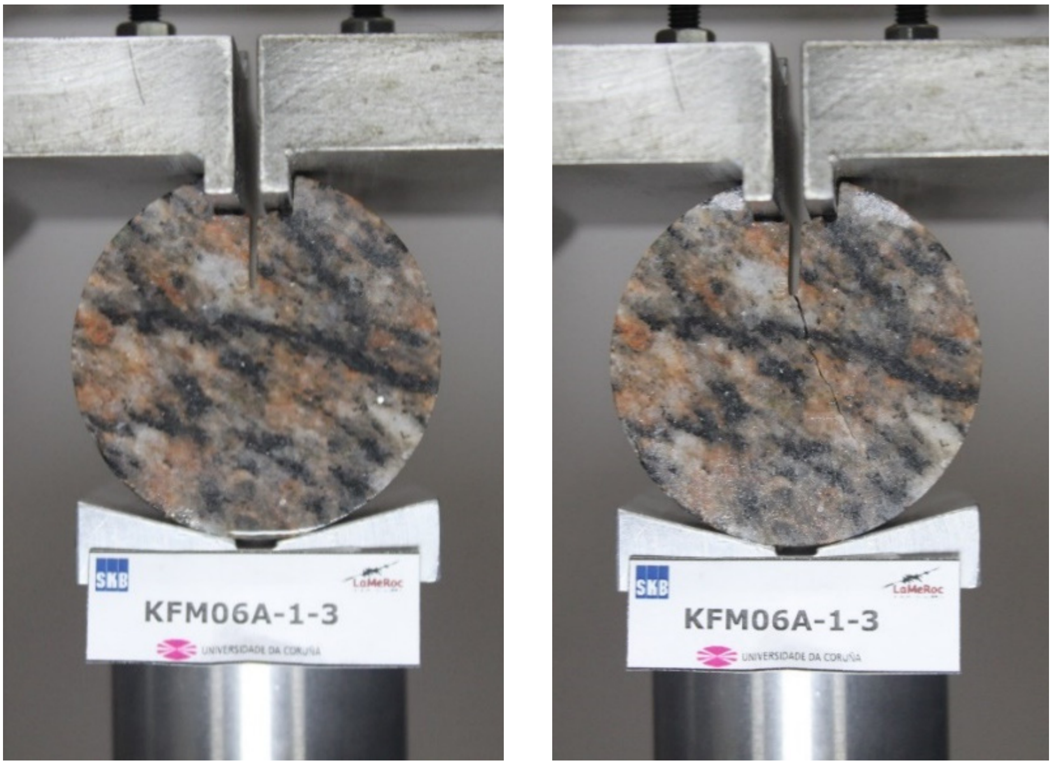

Figure A-0-5. *Sample KFM06A-1-3 before (left) and after (middle right) conducting a pCT test. The K_{IC} value obtained was of 1.61 MPa $m^{1/2}$ obtained for a maximum load of 1.48 kN.*

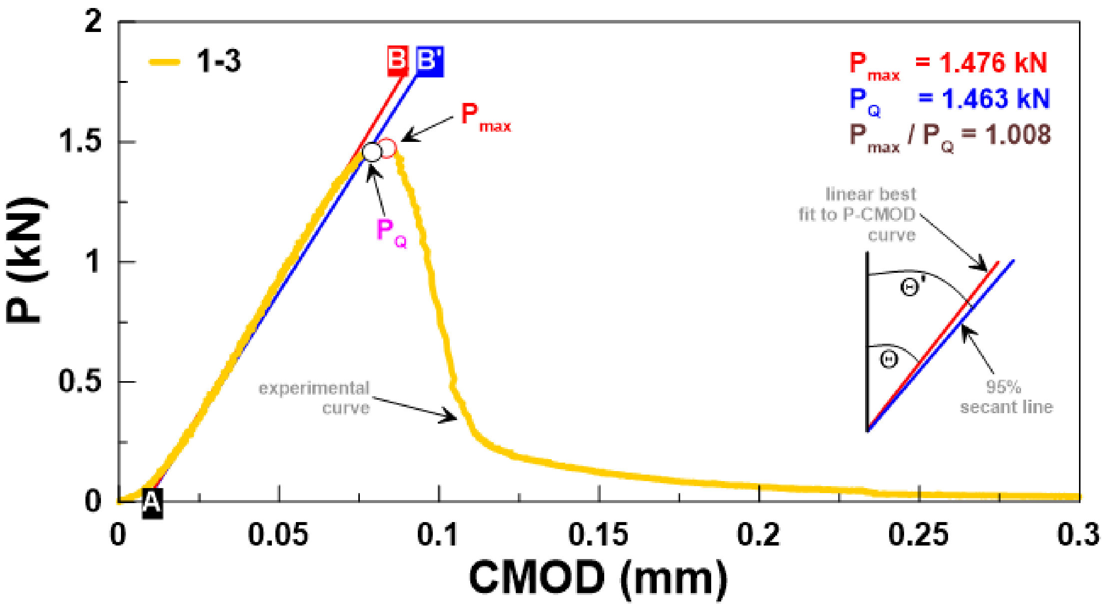

Figure A-0-6. *Experimental results of the pCT test performed with specimen 1-3 and verification of the linearity criterion of the compliance method. See text for explanation Notes: P = applied horizontal load; P_{max} = maximum load; P_Q = conditional load; CMOD = crack mouth opening displacement (≡ load point displacement).*

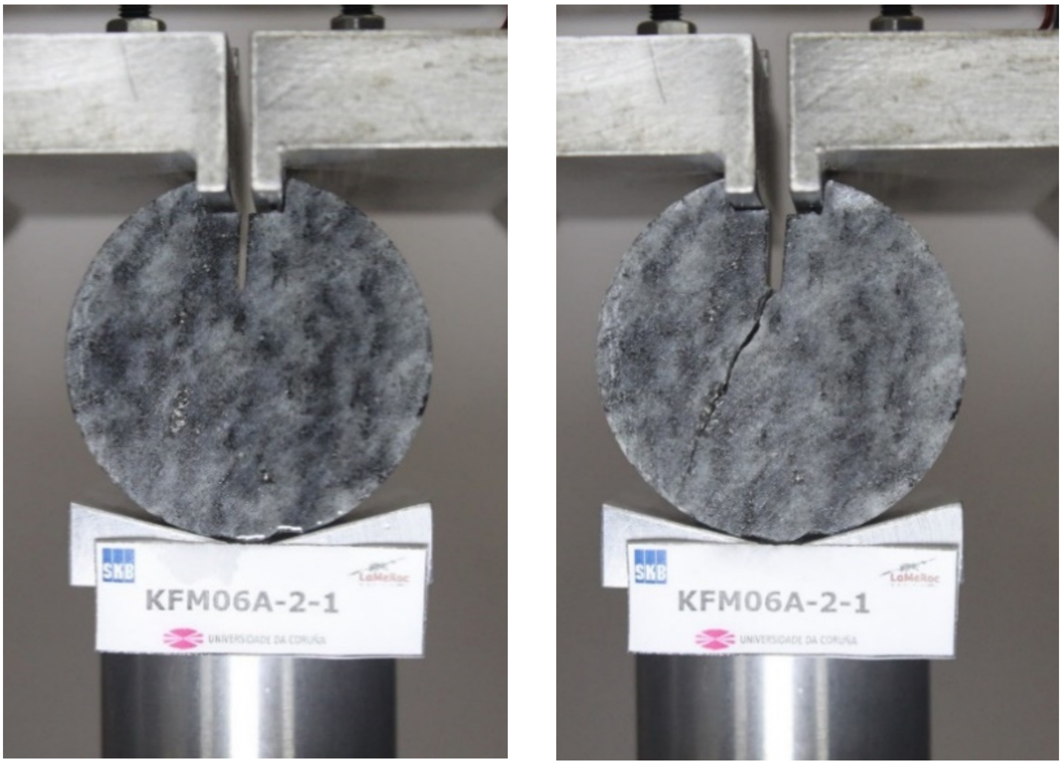

Figure A-0-7. *Sample KFM06A-2-1 before (left) and after (middle right) conducting a pCT test. The K_{IC} value obtained was of 1.52 MPa $m^{1/2}$ obtained for a maximum load of 1.27 kN.*

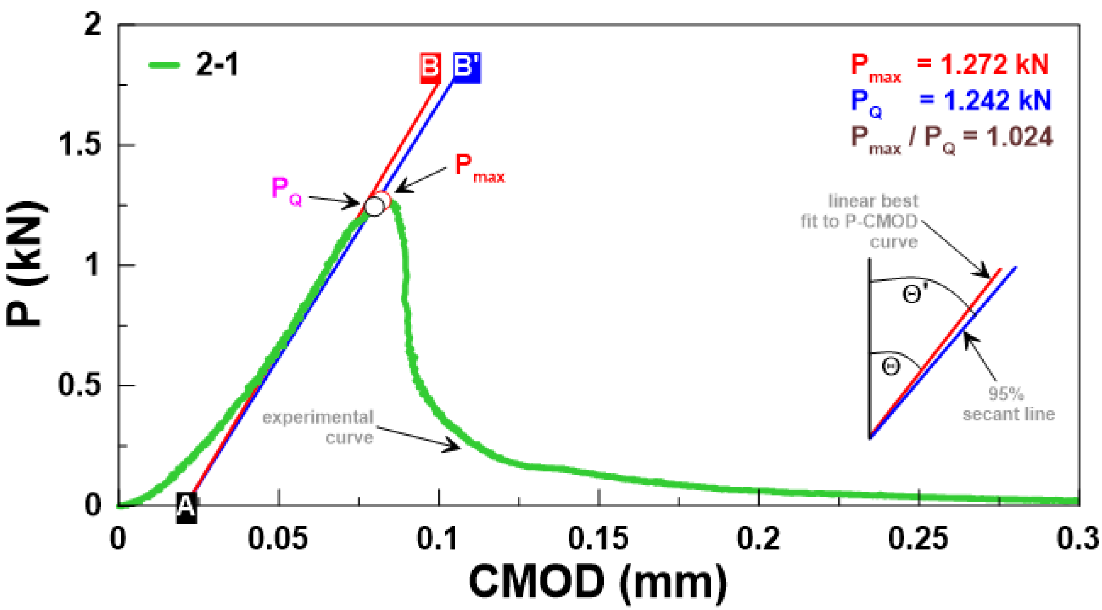

Figure A-0-8. *Experimental results of the pCT test performed with specimen 2-1 and verification of the linearity criterion of the compliance method. See text for explanation Notes: P = applied horizontal load; P_{max} = maximum load; P_Q = conditional load; CMOD = crack mouth opening displacement (≡ load point displacement).*

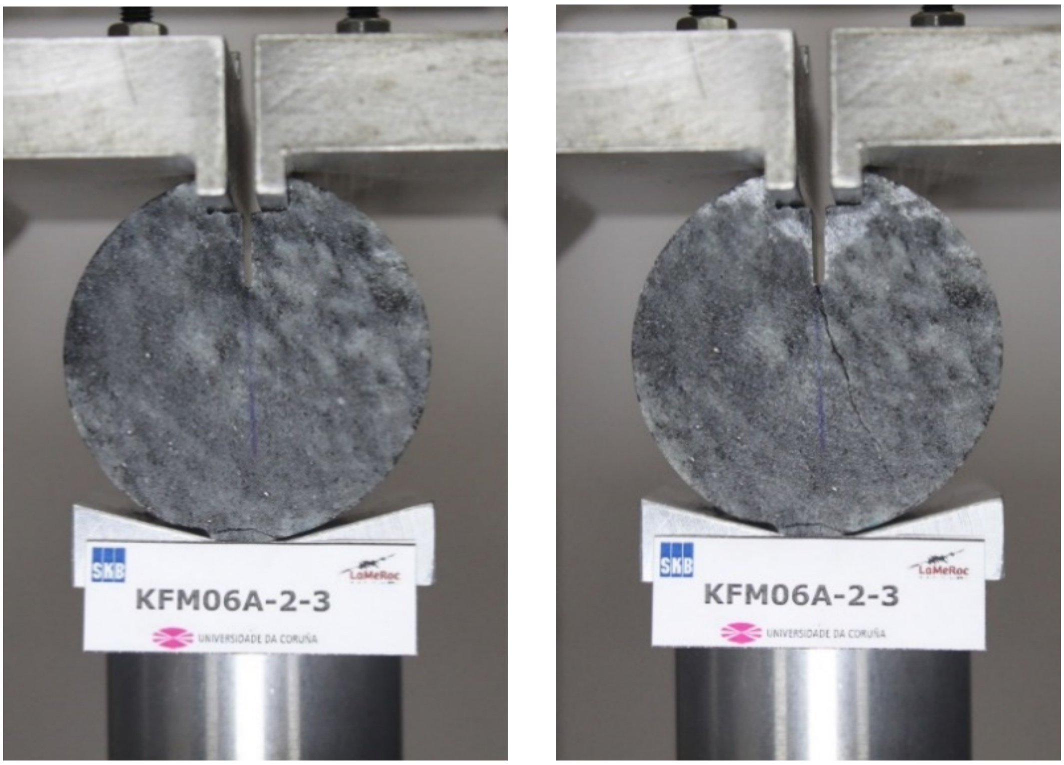

Figure A-0-9. *Sample KFM06A-2-3 before (left) and after (middle right) conducting a pCT test. The K_{IC} value obtained was of 1.84 MPa $m^{1/2}$ obtained for a maximum load of 1.31 kN.*

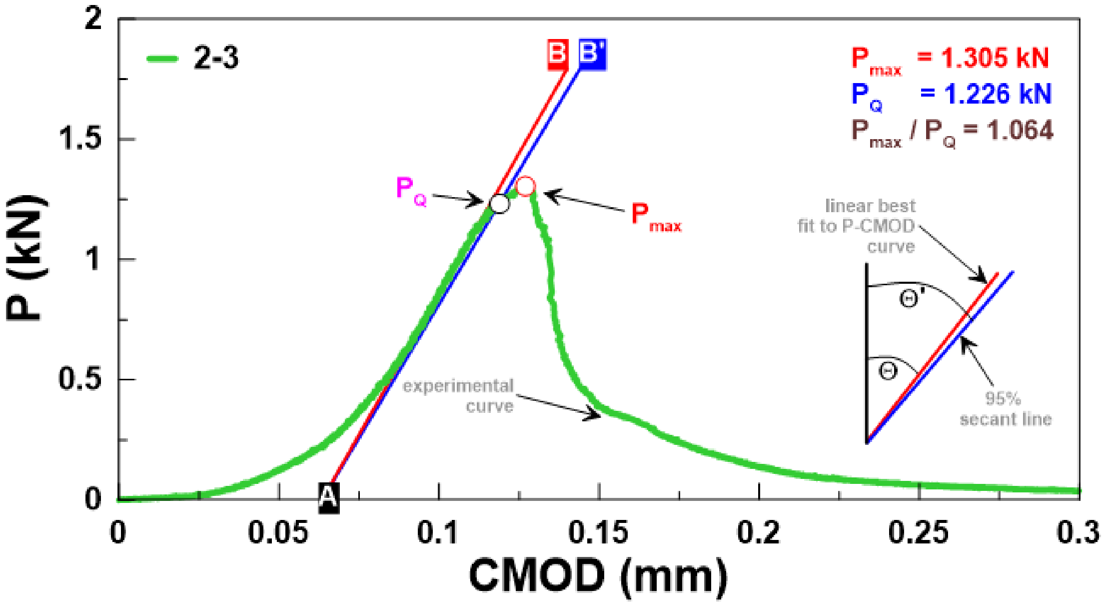

Figure A-0-10. *Experimental results of the pCT test performed with specimen 2-3 and verification of the linearity criterion of the compliance method. See text for explanation Notes: P = applied horizontal load; P_{max} = maximum load; P_Q = conditional load; CMOD = crack mouth opening displacement (≡ load point displacement).*

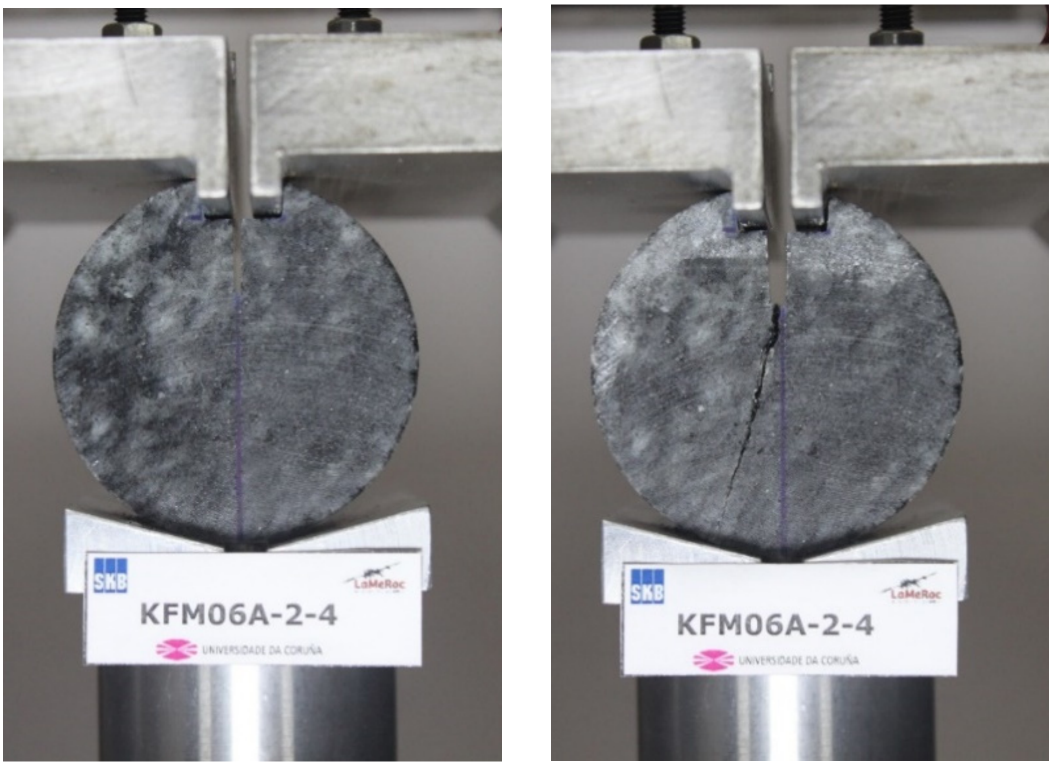

__Figure A-0-11.__ Sample KFM06A-2-4 before (left) and after (middle right) conducting a pCT test. The K_{IC} value obtained was of 1.63 MPa $m^{1/2}$ obtained for a maximum load of 1.44 kN.

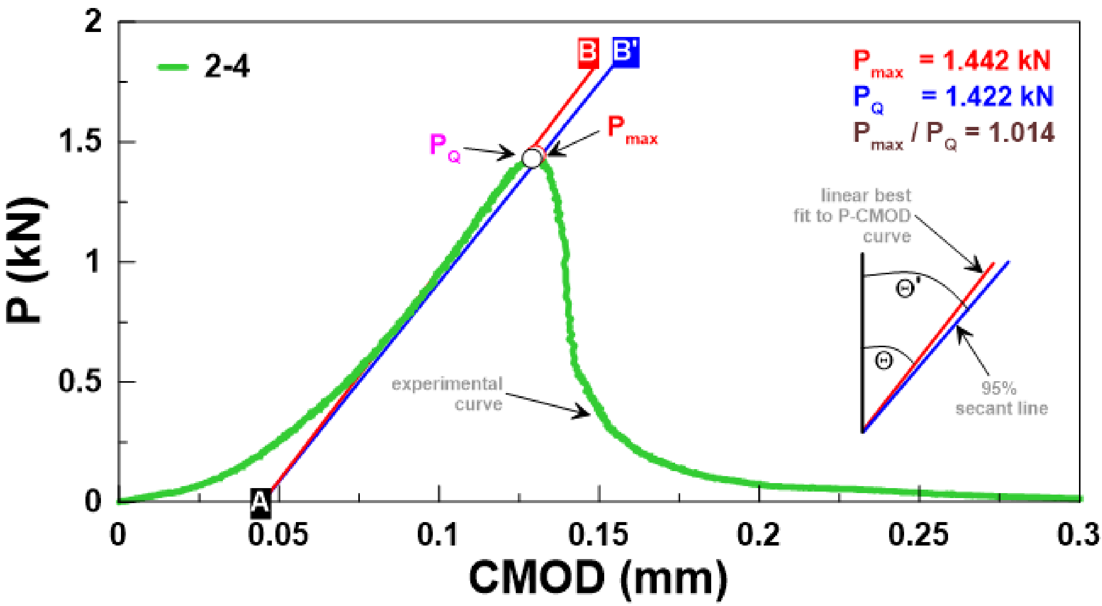

__Figure A-0-12.__ Experimental results of the pCT test performed with specimen 2-4 and verification of the linearity criterion of the compliance method. See text for explanation Notes: P = applied horizontal load; P_{max} = maximum load; P_Q = conditional load; CMOD = crack mouth opening displacement (≡ load point displacement).