# A METHOD FOR THE DETERMINATION OF FRACTURE TOUGHNESS IN CORE SAMPLES CONSIDERING PRESSURE ON THE CRACK FACES

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## ABSTRACT

Método para determinar la tenacidad a la fractura en testigos de corona considerando presión en las caras de la fractura.

En este trabajo se describe un método simple y novedoso para la determinación de la tenacidad a la fractura de la roca (KICKIC), el que resulta adecuado para ser extendido a condiciones de reservorio. De acuerdo con los antecedentes procurados, esta es la primera aplicación de presurización en las caras de la fractura para la medición de KICKIC en rocas. El método propuesto permite una medición de KICKIC más rápida y más extensivamente aplicable que los métodos actualmente disponibles. Primero se describe la concepción del método, que puede ser aplicado en testigos de corona. Luego se describen el diseño y construcción del equipo de medición. Finalmente, se muestra la aplicación y se delinean mejoras adicionales. El método es un avance en el uso más difundido del parámetro KICKIC, que representa una magnitud física de la roca, en lugar de los índices de fracturabilidad, que son solamente fenomenológicos. A menudo se considera que estos índices proveen un valor limitado, y con frecuencia llevan a conclusiones que difieren entre sí.

## INTRODUCTION

Shales are the most abundant of sedimentary rock types, making up 50–80% of sedimentary material worldwide (Chandler *et al.* 2016). They are therefore extremely important in a variety of Earth related topics, including hydrocarbon resources.

The exploration and production of shales steadily increased the quality, quantity and complexity of data used for evaluation and decision making. These considerations allowed for drilling and completion cost reduction, design optimization (e.g., vertical to horizontal wells), productivity enhancement, etc. This improved understanding of shale reservoirs, along with an extensive use of available data, provides a driving force for new experimental methods and associated data analyses.

Due to the extremely low permeability of shale reservoirs, economical production of hydrocarbons from them typically demands that the reservoir is hydraulically stimulated (fractured) prior to production. The successful stimulation of shale reservoirs depends on the availability of important parameters, and knowledge on how they affect the outcome of the fracturing treatment and ulterior productivity of drilled wells. The in situ stress field, pore pressure, fracturing fluid pressure, and the mechanical properties of the rock are of primal importance (Warpinski and Smith 1990).

Among the mechanical properties, some quantification of the resistance to cracking is needed. From linear elastic fracture mechanics of brittle materials, it is known that the fracture toughness KICKIC is one such material property (Anderson, 1994). Fracture toughness is an important parameter influencing hydraulic fracture propagation, in particular for low stress contrasts, low fluid viscosity, and small fractures (Thiercelin *et al.* 1989).

Many researchers considered early on that fracture toughness has typically a negligible effect in hydraulic fracturing, based on the comparison between the energy expended in flow of the viscous fluid and in creating new surfaces during crack propagation (Cleary 1990). Nevertheless, there is some evidence that the values for fracture toughness used in these estimations, which is based on lab conditions, may not be representative of in-situ values. Values of $K_{IC}$ under reservoir conditions may be several times the values usually measured, prompting a reconsideration of its role, the need for more extended data under realistic in situ conditions, and suitable testing methods for obtaining thereof. For instance, the contrast in $K_{IC}$ between adjacent layers may profoundly affect fracture height containment (Thiercelin *et al.* 1989), especially when other height containment mechanisms are absent (Thiercelin 1989).

Despite this importance, fracture toughness data on shales are sparse, and they show significant scatter. The microstructure of shales makes material recovery, preservation, and sample manufacture very difficult, while hindering consistent and reproducible experiments. Recognition of the importance of fracture mechanics concepts, including fracture toughness, is evinced by

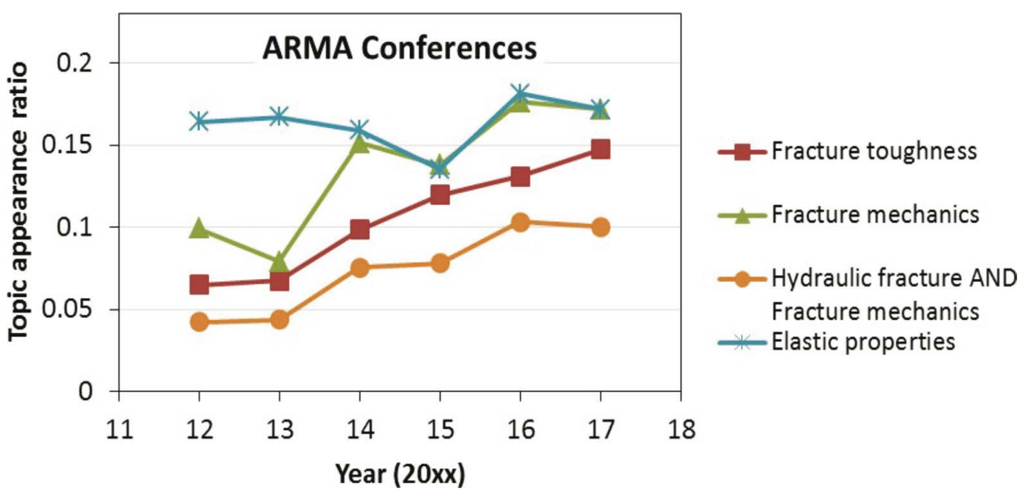


**Figure 1. Appearance ratio of various keywords in ARMA Conferences articles. The increasing relevance of "Fracture" related topics, and in particular of "Fracture mechanics" concepts, is evident.**

the appearance ratio of various "Fracture" related topics and keywords in ARMA Conferences articles (www.onepetro.org), see Fig. 1. Fracture toughness is a physically meaningful parameter, as opposed to the phenomenological frackability or brittleness indexes. These indexes are usually regarded as containing limited value, and they often provide opposite conclusions to each other (Yang *et al.* 2013).

Recommended methods for determining the fracture toughness of rocks based on core samples have been developed (ISRM 1988; Ouchterlony 1989, 1990) by the ISRM Working Group, and other methods have also been conceived. In any case, the application of these and other methods to the measurement of $K_{IC}$ under reservoir conditions, and in particular in shales, is very limited. Schmidt and Huddle (1977) pioneered that work, using Indiana limestone under varying confining pressure. A few other authors performed related work, and very few used both high pressure and high temperature (Al-Shayea *et al.* 2000). In this work we describe a novel simple method for the determination of rock fracture toughness on core samples, which is amenable for extending to reservoir conditions. We first describe the conception of the method, then we describe the design and construction of the testing rig. Finally, we show the application and delineate further improvements.

## Methodology

### Design and construction of the testing rig

The various test methods and specimen configurations used to determine the stress intensity factor KICKIC for these materials involve the application of remote loads, tensile tests, bending tests, etc. Given that the initiation and propagation of hydraulic fractures is mainly controlled by the field of in situ stresses (Healy 2012), it is possible to achieve the same conditions by applying a hydraulic pressure inside a crack that causes its propagation and subsequent breakage. Thus,

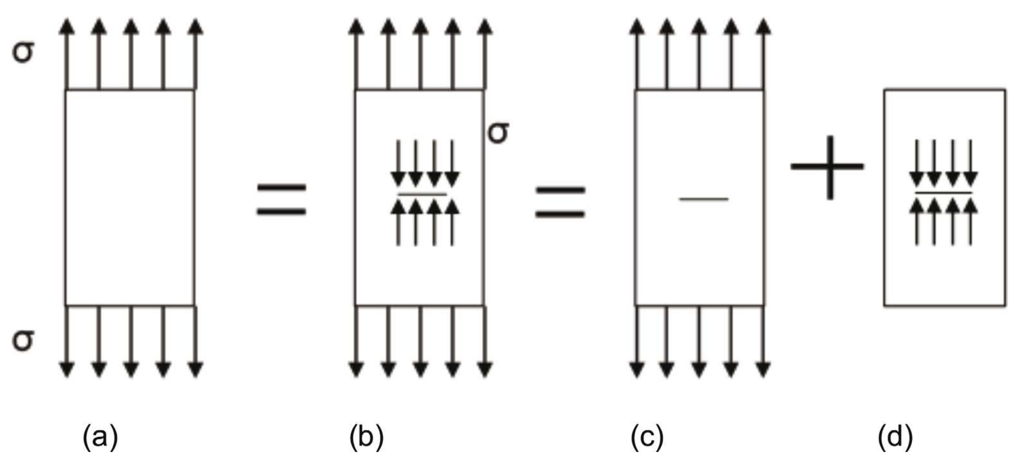


Figure 2: Superposition principle, valid under linear elasticity conditions, applied to the case of a cracked vs. uncracked body.

known correlations between the remote load and $K_{IC}$ can be used to determine the critical fracture conditions. This concept is shown in Fig. 2. Referring subindexes to the subfigures in Fig. 2, since $K_{I(a)}$ is zero, that means that $K_{I(c)}$ is $-K_{I(d)}$. This a result of applying the superposition principle for $K_I$.

Consequently, $K_I$ at the tip of the crack subjected to a remote tensional state σ is equal to that obtained if this remote stress σ acts on the interior surfaces of that same crack, Fig. 3.

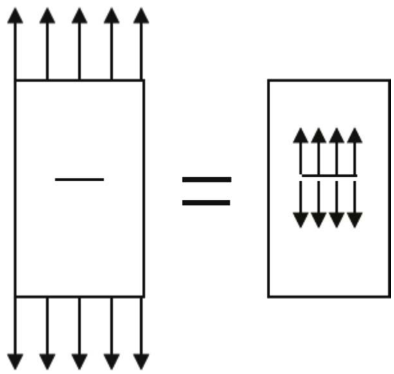

**Figure 3. Result from the analysis by superposition of applied stress intensity from remotely applied stresses vs. pressure at crack faces.**

In other words, the fractomechanically equivalent system to the remote application of loads is limited to the direct and effective application of pressure on the free surfaces of the crack gap. This loading condition is similar to the effects of the injection of fluid with proppant in the processes of hydraulic fracturing.

With this principle, a concept test device was built that allows studying the behavior of these materials in the presence of cracks under the action of hydraulic loads and their dependence on different fluids and proppants used during the process of "fracking" (Fig. 4). Essentially, the

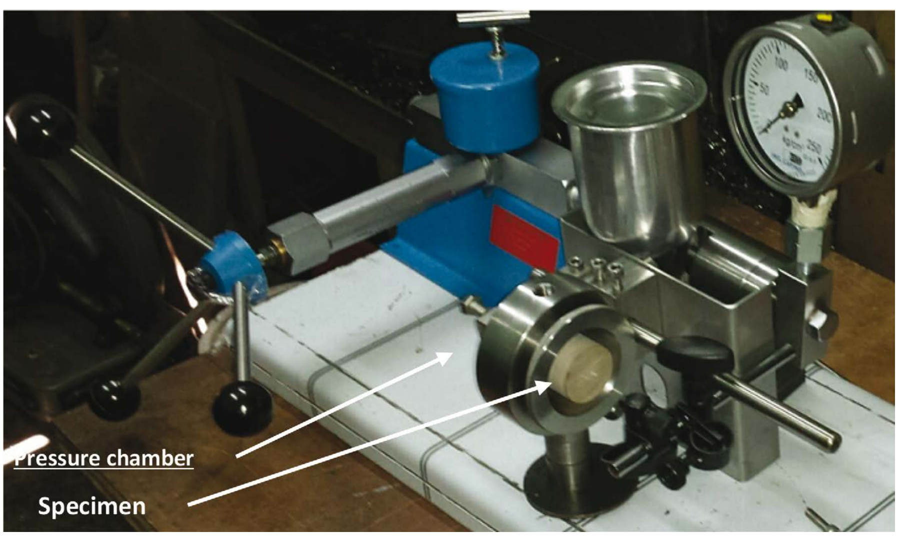


**Figure 4. Testing device.**

device generates a stress field under controlled conditions caused by the action of hydraulic fluid confined at the tip of a machined crack in a cylindrical specimen (Fig. 5). In this way, we have a reliable system of controlled loading on small probes without the need for reactive frames or robust testing machines for the application of remote stresses. Samples surface ground to a D=37.6 mm diameter were adopted.

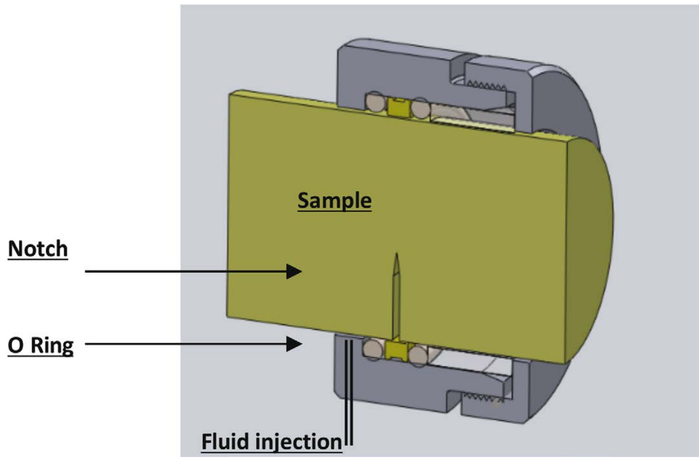


Figure 5. Section showing the specimen seal system.

## Testing procedure

The mechanical properties of a material characterize its response under the application of external mechanical loads, and they are determined through laboratory tests that intend to reproduce the operational conditions of the material. Some factors, such as the nature of the load applied, its duration and environmental conditions (temperature, humidity, etc.) are determining factors in the behavior of materials (Rodríguez Pérez 1993).

Determining mechanical properties of materials from tests involves calculating said values from the measured variables. When these values are independent of the geometry of the sample and the way the load is applied, the determined value can be defined as a property of the material. Then the results of the test give basic information to predict the behavior and failure of a material in engineering applications. The properties obtained can be used under loading conditions different from those of the test, provided that the response is governed by the same mechanism.

In the present case, the target quantity is the critical stress intensity factor of rocks $K_{IC}$, derived from the hydraulic fracture pressure of the specimen in the experimental device. $K_{IC}$ is calculated using the shape correction factor proposed in API 579 standard, which explicitly considers the geometry used in this test (Fig. 5) and considering the superposition principle that equates the case of remote tensile stress applied to the external faces of the cylindrical sample to the interstitial pressure inside de crack.

Natural rock generally has a large scatter in properties, even among samples extracted from neighboring material. To reduce the uncertainty in the elaboration of the testing procedure, the use of cementitious material--uniform in constitution, setting time, etc.–is proposed.

Unlike the case of metals, it is in general not possible to generate a controlled fatigue precrack in rocks or cement based materials prior to testing for the determination of $K_{IC}$. Since the actual radius of the tip of the notch affects the value determined for $K_{IC}$, it is appropriate to evaluate quantitatively this dependence, and to determine the practical limits from which the results converge to a $K_{IC}$ value independent of the geometry.

Specimens with variable notch depth a ranging from 4 mm to 14 mm, and with notch bottom radii r 0, 1 mm and 1.5 mm were tested. Obviously, for implementation issues can not comply with this requirement to generate notches, notch width 0.5 mm was used, the minimum value compatible with abrasion technique used. The 1 and 1.5 mm notch bottom radii were achieved by cross-drilling at the required distance and subsequent milling by abrasion of the remaining ligament.

## Results

Fig. 6 shows the results of the present tests, where the value of $K_{IC}$ determined for each test is plotted against the ratio a/D. The determination of $K_{IC}$ from the burst pressure was performed according to API 579, App. C. The analytical solution for the calculation of $K_{IC}$ considers zero crack width (planar defect):

$$K_{IC} = (M_m \sigma_m + M_b \sigma_b)\sqrt{\pi a} \quad ,$$

where $M_m$ and $M_b$ are membrane and bending components of stresses in the section. In the present conditions, $\sigma_m$ is the applied fluid pressure and $\sigma_b$ is zero. The shape factor for the cracked rod is

$$M_m = 0.926 - 1.771\vartheta^1 + 26.421\vartheta^2 - 78.48\vartheta^3 + 87.97\vartheta^4 \quad (\vartheta = a/D).$$

## Analysis of results

The values determined for $K_{IC}$ show a clear dependence on the depth of the notch, for all values of notch radius. The values obtained are well within known values of $K_{IC}$ for cement paste and mortars, $K_{IC} \approx 0.3\text{-}1.0$ MPa $m^{1/2}$, (Brown and Pomeroy 1973). As expected, an increasing radius of the bottom of the notch leads to increasing values of $K_{IC}$. For non-zero radii, the value

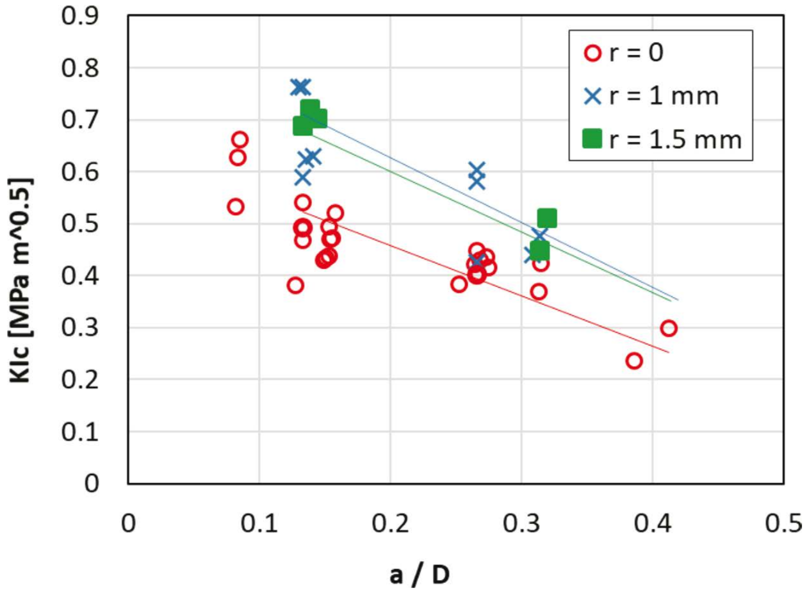


Figure 6: Values of KICKIC determined for a range of notch depths a/D and varying the notch radius.

obtained is not representative of the fractomechanic property, but it can be used comparatively among different materials, if the notch is standardized.

The dependency of the values of $K_{IC}$ with the geometry of the notch may stem from at least three factors: a) the non-zero thickness of the notch, since shape factors are defined for planar defects (without separation between fracture faces); b) notch bottom with non zero actual radius, and c) the possible effect of radial compression on the material confined between the seals of the pressure chamber.

Factors a) and b) can be included in the $K_{IC}$ formulation by appropriately modifying the shape factor $M_m$, according to the actual geometry. This correction can be made by determining the value of $K_I$ by finite elements simulations, an ongoing work. This effect is of a purely mechanical nature.

The remaining divergence, after applying the corrected shape factor, will depend on other variables such as the dependence of $K_{IC}$ on the hydrostatic component of the stress state generated in the sample. Known values of the effect of confinement pressure on $K_{IC}$ of a variety of rocks are in the range 0.03 0.12 m-1/2 (Al Shayea 2002). An initial evaluation of our data indicates similar values, suggesting that this is a likely cause for the observed dependence of $K_{IC}$ on notch depth. Work is under way to further evaluate this effect. It is worth noting that this effect stems from the constitutive behavior of the material, thus it cannot be evaluated solely on the basis of numerical simulations.

## Conclusions and perspectives

Based on established principles of linear elastic fracture mechanics, an experimental facility was designed and built to measure the fracture toughness $K_{IC}$ of rock samples. A salient feature of the design is that it is well suited for using with notched core samples, with a small volume of expended material per test. The system is easily adaptable to the study of the effect of variable hydraulic loads, which is considered important to analyze the action of the fluids and proppants against partial closure of cracks. In addition, the effect of reservoir conditions (pressure, temperature) on $K_{IC}$, often considered of primal relevance in the outcome of the stimulation treatment (Thiercelin *et al.* 1989) could be incorporated with suitable cells.

The analysis of the effect of notch depth and notch edge radius showed values of $K_{IC}$ decreasing with both a/D and r. A number of factors were identified as possible causes for this dependence, to wit:

a) Non-zero thickness of the notch.
b) Non-zero radius of the notch edge.
c) Effect of confinement of the sample between the seals.

Work is under way to clarify these aspects and to develop a method that provides geometry independent values of $K_{IC}$, including finite element simulations. There are strong indications that consideration of factor (c) would lead to the sought for $K_{IC}$. Despite these areas where improved knowledge is required to bring the technique into its final applicable procedure, the values obtained correspond with known values of $K_{IC}$ for cement paste and mortars, $K_{IC} \approx 0.3\text{-}1.0$ MPa $m^{1/2}$, (Brown and Pomeroy 1973), thus lending confidence to the method.

The present method is amenable to incorporating considerations on the anisotropy of rocks, much in the same way as ISRM (1988) and Ouchterlony (1990) did. This will be taken upon at a later stage.

## Nomenclature

$K_I$: Stress intensity factor.
$K_{IC}$: Mode I fracture toughness.
D: Sample diameter.
a: Notch depth.
r: Notch radius.
$M_m$: Shape factor for the membrane stress.
$M_b$: Shape factor for the bending stress.

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## CITED REFERENCES

Al-Shayea, N., K. Khan and S. Abduljauwad, 2000, “Effects of confining pressure and temperature on mixed-mode (I-II) fracture toughness of a limestone rock”, Rock Mech. Mining Sci. 37, 629–643.

Al-Shayea, N., 2002, “Comparing reservoir and outcrop specimens for mixed mode I–II fracture toughness of a limestone rock formation at various conditions”, Rock Mech. Rock Engng. 35(4), 271–297.

Anderson, T.L., 1994, “Fracture mechanics – Fundamentals and applications”, 2nd. Ed., CRC Press.

API 579 – 2000, “Recommended Practice for Fitness for Service, Appendix C, Compendium of stress intensity factor solutions”, American Petroleum Institute (API).

Brown, J.H., and C.D. Pomeroy, 1973, “Fracture toughness of cement paste and mortars”, Cement Concr. Res., 3, 475–480.

Chandler, M.R., P.G. Meredith, N. Brantut, and B.R. Crawford, 2016, “Fracture toughness anisotropy in shale”, J. Geophys. Res. Solid Earth, 121, 1706–1729.

Cleary, M.P., 1980, “Analysis of mechanisms and procedures for producing favorable shapes of hydraulic fractures,” SPE 9260-MS presented at SPE Annual Technical Conference and Exhibition, Dallas, Sept. 21-24.

Healy, D., 2012. “Hydraulic fracturing or fracking: a short summary of current knowledge and potential environmental impacts,” Science, Technology, Research & Innovation for the Environment Programme.

International Society of Rock Mechanics (ISRM), 1978, “Suggested methods for determining tensile strength of rock materials”, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 15, 99–103.

International Society of Rock Mechanics (ISRM), 1988, “Suggested methods for determining the fracture toughness of rock”, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 25, 71–96.

Ouchterlony, F., 1989, “On the background to the formulae and accuracy of rock fracture toughness measurements using ISRM standard core specimens”, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 26(1), 13–23.

Ouchterlony, F.,1990, “Fracture toughness testing of rock with core based specimens”, Eng. Fract. Mech. 35(1/2/3), 351–366.

Rodríguez Pérez, J., 1993, “Análisis y desarrollo de metodologías para la obtención de propiedades mecánicas de materiales a altas velocidades de deformación y a alta temperatura”, Departamento de Física de Materiales, Universidad Complutense de Madrid.

Thiercelin, M., 1989, “Fracture Toughness and Hydraulic Fracturing”, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 26, 177-183.

Thiercelin, M., R. Jeffrey, and K.B. Naceur, 1989, “Influence of fracture toughness on the geometry of hydraulic fractures”, SPE-16431-PA presented at SPE Production Engineering, pp. 435–442, Soc. of Petrol. Eng.

Schmidt, R.A., and C.W. Huddle, 1977, "Effect of confining pressure on fracture toughness of Indiana limestone", Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 14, 289-293.

Warpinski, N., and M. Smith, 1990, "Rock mechanics and fracture geometry", in Recent Advances in Hydraulic Fracturing, edited by J. Gidley *et al.*, pp. 57–80, Soc. of Petrol. Eng., Texas.

Yang, Y., H. Sone, A. Hows and M.D. Zoback, 2013, "Comparison of brittleness indices in organic rich shale formations", ARMA 13-403.