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DOUBLE TORSION TESTING MACHINE TO DETERMINE THE SUBCRITICAL FRACTURE INDEX IN ROCKS

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ABSTRACT

This paper discusses the design methodology applied to build a testing machine to determine the subcritical fracture index in a rock, based on double torsion testing in order to characterize naturally fractured formations such as those located in the Colombian Llanos Foothill Basin. These formations have been subjected to cyclic loads over time, causing fractures that trend to spread at subcritical stress intensity values. Similarly, it presents the results of testing conducted on nine specimens of the Tambor Formation from 2 different outcrops to establish the testing traceability in the equipment.

Keywords: *Subcritical fracture index, Stress intensity factor, Critical load speed.*

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RESUMEN

El presente artículo desarrolla la metodología de diseño para construir un banco de pruebas que permita determinar el índice subcrítico de fractura en una roca a través del ensayo de doble torsión, con el objeto de caracterizar formaciones fracturadas de origen natural como las ubicadas en la Cuenca de Piedemonte Llanero Colombiano. Estas formaciones han sido sometidas a cargas cíclicas a través del tiempo las cuales ocasionan fracturas que tienden a propagarse a valores de intensidad de esfuerzos menores a los críticos. De igual forma se presentan los resultados obtenidos en las pruebas realizadas en nueve probetas de la Formación Tambor pertenecientes a 2 afloramientos diferentes, llevados a cabo con el fin de establecer la trazabilidad de los ensayos realizados en el equipo.

Palabras claves: *Indice subcrítico de fractura, Factor de intensidad de esfuerzos, Velocidad de carga crítica.*

RESUMO

O presente artigo desenvolve a metodologia de desenho para construir um banco de provas que permita determinar o índice subcrítico de fratura em uma rocha através do ensaio de dupla torção, com o objetivo de caracterizar formações fraturadas de origem natural como as localizadas na Bacia de Piedemonte Llanero Colombiano. Estas formações foram submetidas a cargas cíclicas através do tempo as quais ocasionam fraturas que tendem a propagar- se a valores de intensidade de esforços menores aos críticos. Igualmente, são apresentados os resultados obtidos nas provas realizadas em 9 (nove) provetas da formação Tambor pertencentes a 2 (dois) afloramentos diferentes, realizadas com o fim de estabelecer a traçabilidade das provas no equipamento.

Palavras chaves: *Índice subcrítico de fratura, Fator de intensidade de esforços, Velocidade de carga crítica.*

1. INTRODUCTION

At present, there are no geomechanical models in Colombia to characterize subcritical fractured formations. This initiative implemented the subcritical crack growth model used by the University of Austin, Texas (Holder, Olson & Zeno, 2001), which relates crack velocity with rock toughness in order to estimate this subcritical fracture index (SCI) for which a testing machine was designed and built.

SCI is a parameter that can help determine if a natural formation is either susceptible to crack or if it is already cracked, and therefore it can accurately estimate the crack density of the formations to be drilled or produced from. SCI is based on the use of the fracture scale thesis which states that at high values of index, there will be sets of dispersed cracks that may be separated by large or small distances and at low values of index, there will be smaller sets of cracks that trend to follow a pattern because their distance of separation is smaller (Holder *et al.,* 2001).

The studies published by Park and Nara (2006) suggested the use of real field data in order to characterize the different types of rocks. However, the authors never established the equipment or technology used to conduct testing and determine stress intensity factors. They did not propose a geomechanical model nor even consider validating it, because the rock properties were not available.

This paper presents a bibliographic review of rock testing methods used to determine prototype design requirements as published by Sun, and Ouchterlony, (1986). Then, the theory regarding the double torsion testing is described, followed by the design and construction of the prototype and the presentation of the results obtained from 9 specimens sampled from 2 different outcrops, to estimate traceability in the testing machine.

Geomechanical model

The geomechanical model used to estimate fracture density of rock formations is based on subcritical crack growth. This model is suitable to the fracture condition of rocks because cracks can develop and spread slower than rupture rate of intact rock and besides of this, subcritical crack growth states the condition in which the rock is subjected to long load periods with a stress intensity factor *(KI)* lower than the critical value of the material's stress intensity factor. *(KIc)*, and where the crack spreads at those values of *(KI) < (KIc)* (Atkinson, 1984), (Atkinson & Meredith, 1987). Now, fracture toughness in this model is determined by the double torsion testing suggested by Gerry and Outwater, (1969) and used by Kies and Clark (1969), to determine the fracture energy of fragile materials as well as adhesive joints (Outwater & Gerry, 1966).

Principle of Double Torsion Testing

The test suggests the use of flat samples loaded with perpendicular shear force at the surface as illustrated in Figure 1. A load is applied on the sample and should remain constant initially in order to start the crack spread without changing the stress intensity factor (Ciccotti, 2000). The value of stress will depend, in first place, on the geometry of the sample, its stiffness and the critical load under which the crack spreads (Cho & Gent, 1985).

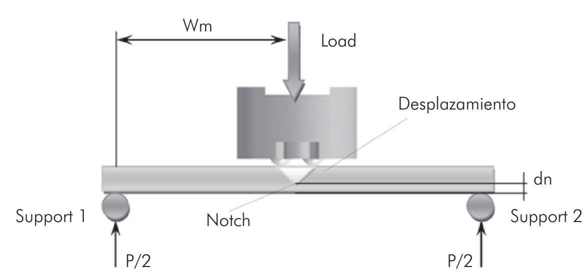

Figure 1. General Outline of Double Torsion Testing. Load direction is vertical, applied directly over edges of the crack on the rock. The rock crack has a v-notch geometry and it is located at the middle of the rock sample. The rock sample edges are supported by a coupled of rigid rods. Displacement and applied force are meassured and controlled to evaluate *KI* and *KIC* on the sample

The critical stress intensity factor *KIC* of the sample is measured when the load required to fracture the rock begins to decrease significantly, which means that it begins to deform faster and more easily. In order to determine *KIC*, a stress intensity factor *KI* has to be calculated, given by the following expression (Atkinson & Meredith, 1987):

$$K_I = P * W_m * \sqrt{\frac{(1+V)}{W*d^3*d_n}}; \quad (1)$$

Similarly, critical crack velocity is defined when *KIC* is registered, which is the maximum rate at which the crack spreads. Once *KIC* is observed, in addition to the decrease in the load being applied on the sample, the crack begins to spread faster and more easily, which is when critical fracture velocity is evidenced.

The function which states that the fracture spreads at values of *KI<KIC* was suggested by Atkinson and Meredith (1987), it calculates the subcritical fracture index, known as subcritical crack growth and establishes that the propagation rate for subcritical crack growth can be described as follows:

$$V = A * K_I^n \quad (2)$$

Similarly, the fracture velocity in the experiment can be determined by load variation values over time using the *Equation 3*, (Williams & Evans, 1973) in which the value of ϕ represents the crack inclination angle, a, crack length, measured on the front surface of the sample and perpendicular to the application of the load.

$$V = \phi a P \frac{1}{p^2} \left(\frac{dP}{dt}\right) \quad (3)$$

In this particular case, the function suggested by Holder *et al.* (2001) establishes that ϕaP can be approximated by a constant *C(C=y/a)* that relates the compression load displacement applied on the sample and the variation in crack length. The load variation relationship over time *dP/dt* can be kept constant by increasing the load at defined intervals or by taking data at defined intervals.

Testing machine Design Parameters

According to Wittaker (1992) and Budynas and Nisbett (2008) to desing a testing machine certain characteristics must be defined (portability, load capacity, sample size). In this case the testing machine should meet the follo-wing characteristics: First, total weight should be under 25kg. Second, the system should be portable to facilitate transport and installation, while guaranteeing stability in operating conditions. Third, it must have the capacity to hold flat, thin, rectangular samples as illustrated in Table 1.

In order to accomplish these objectives, a modular design has been suggested to include the functions of securing, applying and measuring the load, along with the displacements generated in the sample.

Table 1. Dimensions in mm

	Sample 1	Sample 2
Length	63,5 - 70	100 -150:
Width	24,5 - 30	80 -100
Thickness	1,8 - 3	3 - 5

Structural Module

This module carries out the functions of storing the sample and holding the load module. It consists of two side plates, the top plate and the bottom plate, all made of AISI-304 stainless steel, connected by stud bolts as illustrated in Figure 2.

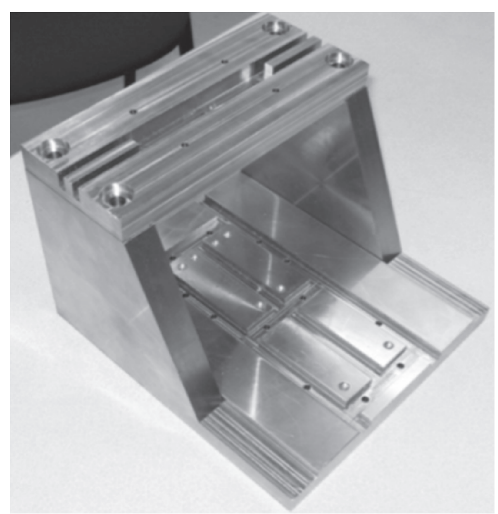

Figure 2. Double torsion testing machine Structural Frame. The Structural frame is able to support different rock sample geometries and lithologies. The design dissipates energy on the bottom plate in a safety manner

A digital micrometer is coupled on the bottom plate (Figure 3), in a cavity that allows adjustment and alignment for proper load application, in accordance with the requirements of the double torsion test. This guarantees that the sample is resting on 4 points located on the bottom plate of the structure, thus favoring fracture propagation by the notch made beforehand in the middle of the sample, as illustrated in Figure1.

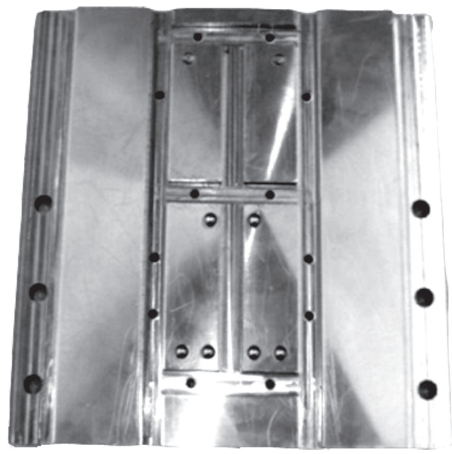

Figure 3. Sample port top view, it is the base to place the samples during testing, the rounded holes are used to place steel spheres to be used as fixed support for axial load transmission which can be adjusted to different sample sizes. The central chanel is a guide to ease the movement of fracture on the rock sample

Load Module

The load module consists of a digital micrometer which applies the load and measures the displacement generated on the sample while testing. It also has 2 components to transfer the load to the sample. The first component is a joint that connects micrometer with the load cell, and the second component is a joint which connects the load cell with the steel spheres to apply the load on the sample, see Figure 4. In addition to this, the sensor movement has to be restricted to the vertical direction, In order to do so, the micrometer's measurement spindle is secured to the ball bearing, which is connected to the coupling base.

Control Module

The purpose of this module is to read and control the variables measured during the test. It consists of an S35 100 lbs load cell, which works at compression and measures the load applied on the sample during testing. To select the load cell the following factors were took into account: rock load measurement interval, availability on the local market and type of load application. It is also important to point out that the micrometer selected for this application is used to assure the accurate axial displacement of the load cell and constrain the movement

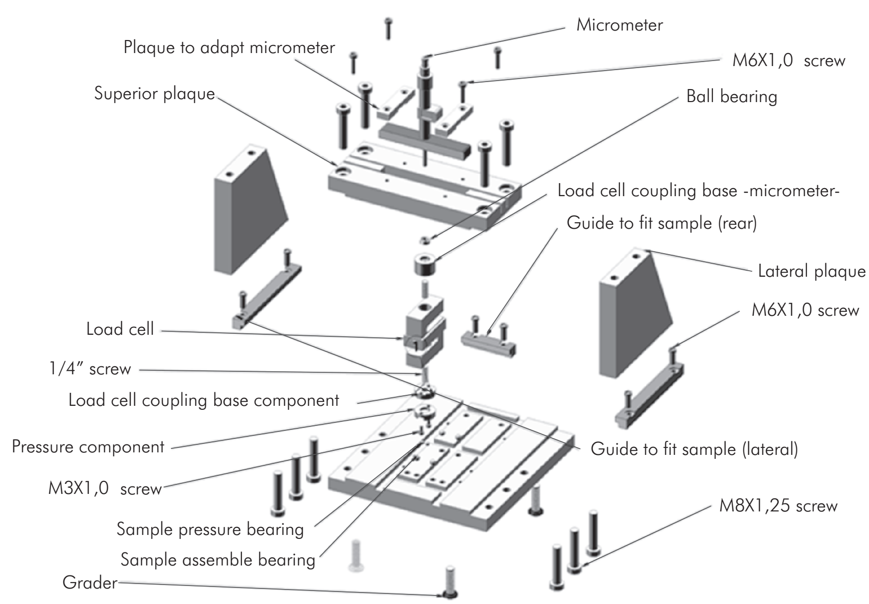

Figure 4. Equipment Components. It shows, lateral, bottom and top supports which act as frame load, the instrumentation used is a load cell and depth micrometer, and a series of steel spheres to transmit the load properly

on a contact point over the sample through a steel sphere. In order to make the data recording and transference easy and standard, a data acquisition port to obtain information in real time was implemented.

This module also has a component to receive data from the load cell and the digital micrometer through the OPTO-22 "SNAP PAC I/O unit". The data are processed with a software designed using the OPTO-22 programming language to calculate the subcritical crack index. It is important to mention that the signal of the load cell goes through a signal conditioner before processing, to assure an adequate signal transference 2 different voltage sources were used.

After creating the parameterized model in SolidWorks, as illustrated in Figure 4, manufacturing was planned in 3-axle CNC equipment, which carried out the processes of smoothing and polishing, drilling, cavities, outlining and, last but not least, alignment of faces and edges.

Machine Assembly

Once the structural module is built and the couplings and the components to apply the load are manufactured, the equipment must be assembled along with the load cell, the micrometer and the elements of the data acquisition system to form a serial circuit using a TRF 110/24 VAC, as illustrated in Figure 5.

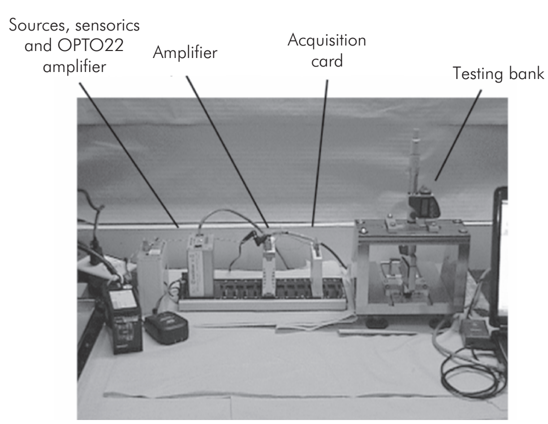

Figure 5. Final assembly of electronics, instrumentation and load frame. Semi-automated control is applied to the testing machine. Data acquisition is done using OPTO 22 protocols, penetration and axial load is applied manually

2. EXPERIMENTAL PROCEDURE

Rocks from the Tambor Formation Outcrop were used to validate the test, from which 9 samples were prepared using ASTM-D4543-08 standard, with the respective characteristics and dimensions listed in Table 1, as illustrated in Figure 6.

Figure 6. Sample before testing. Sample preparation procedure includes polishing the sample end faces and cut a v notch on the principal axe of sample. Dimensions of rock are as follows: length 63,21mm, depth 1,96 mm, width 25,34 mm, V-notch is a cut

After preparing the sample, it was mounted on the workbench (Figure 7). During this part of the process, it was verified that the samples were always placed properly on the stands to make the respective adjustments to begin testing.

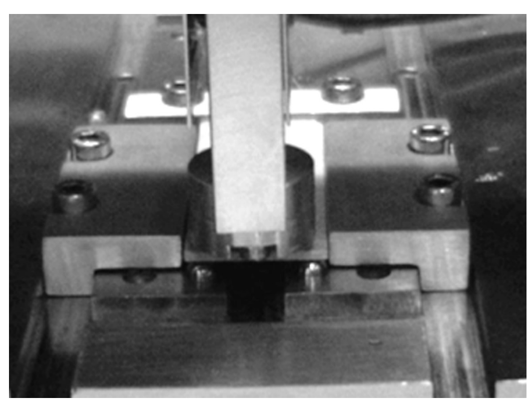

Figure 7. Sample placement on the equipment. Sample has to place equally distanced from the steel spheres and adjusted on the testing machine cavity

During testing, it was observed that the sample always began to crack at the weakest point which was the notch made on the sample, as illustrated in Figure 8.

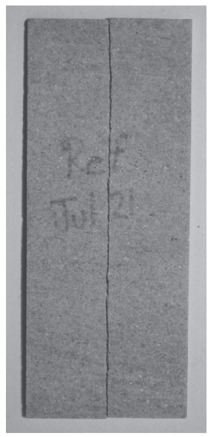

Figure 8. Sample after testing. At the end of test the fracture has propagated all over the main axe of the sample

3. RESULT ANALYSIS

After capturing the data, the critical stress intensity factor *KIC* was determined based on the values obtained in chart *KI* over time as illustrated in Figure 9 and Figure 10 for each of the tests.

The value taken is the value where the crack begins to spread more quickly and the value of the load applied begins to drop.

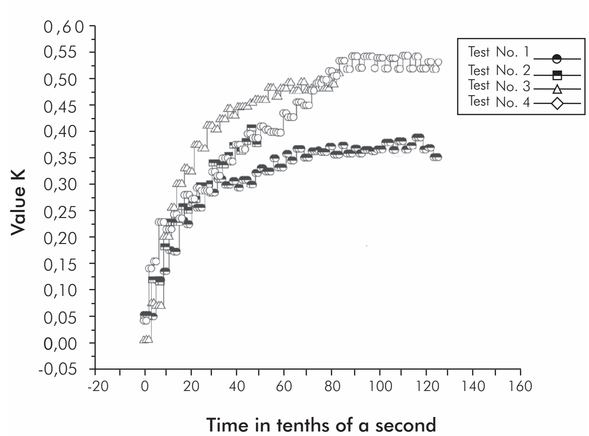

Figure 9. Stress Intensity Factor over Time. Stress intensity increases progressively as time passes by up to the moment in wich the load generates fracture propagation

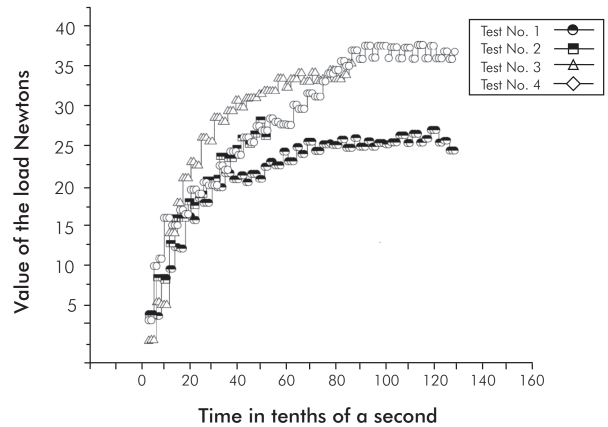

Figure 10. Load Value over Time. Similarly, to stress intensity. Load increases as time goes, load peak corresponds to the moment in which fracture propagates, load decrease follows fracture propagation

Once the critical velocity and intensity values are calculated, the subcritical crack index can be determined as illustrated in Figure 11 and Figure 12, and shown in Table 2.

Table 2. Results in the 2 Tambor Formation Outcrops

	ISF	DEV	Mean Error	Lower Bound 95%	Upper Bound
First	15,25	2,217	1,108	11,721	18,778
Second	24,4	2,007	0,927	21,825	26,974

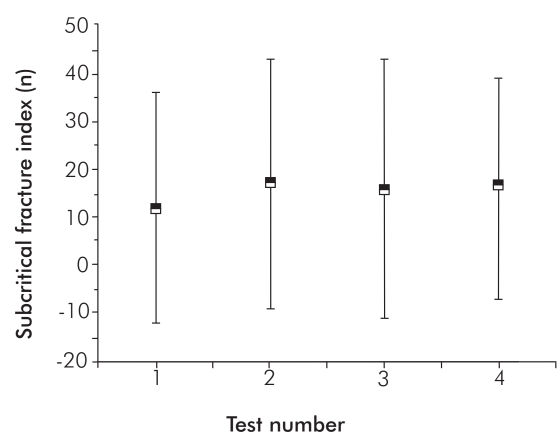

Figure 11. Subcritical Fracture index in Samples from First Tambor Formation Outcrop. SCI has an average value of 16. Dispersion is not significant

The results show that for the first Outcrop, SCI is in the range from 12 to 17. In the case of the second Outcrop, it is between 22 and 27. This difference may be due to the rock's possible cut planes according to Holder *et al.* (2001) and the fact that the plugs have been removed. In general, you could say that SCI for the Tambor Formation is low because none of the values obtained is over 30. Therefore, it can be stated that the Formation is prone to cracking.

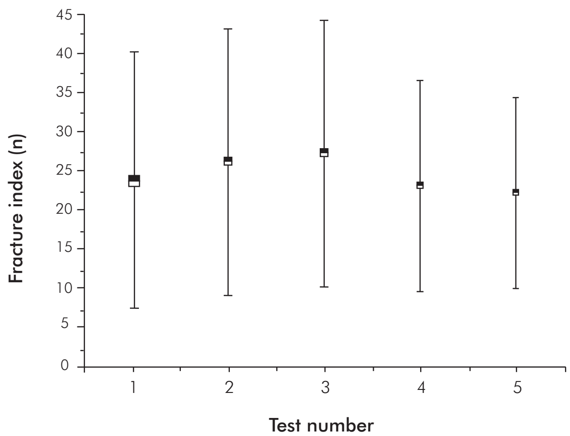

Figure 12. Subcritical fracture index in Samples from Second Tambor Formation Outcrop. SCI average is 25, results dispersion can be significant

4. CONCLUSIONS

- It is inevitable to find dispersion in the results, to determine the value of this property in a porous medium. Nevertheless, it was found that the values of the deviations in the propagation velocities and stress intensity factors in both Outcrops are low, although the respective SCI values are different.

- It should be taken into account that the stress and deformation conditions to which the rock is subjected will vary depending on their location. Therefore, results may slightly vary, even in rocks from the same formation.

- Although a SCI value of 25 would lead to infere that the values indicate a rock whose behavior is related to formations with high fracture density, spaced regularly and spreading at the same time, it is important to point out that it was observed that the tool used to measure displacement and load is not sensitive enough to detect changes in crack geometry when the latter is applied. This means the portability of the prototype may be compromised upon attempting to establish a more real SCI value.

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REFERENCES

ASTM-D4543-08. Standard Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerances.

Atkinson, B. K. (1984). Subcritical crack growth in geological materials. *J. Geo. Res.* 89 (B6), 4077-4114.

Atkinson, B. & Meredith, P. G. (1987). *The theory of subcritical crack growth with applications to rocks and minerals, in Fracture Mechanics.* Academic Press, London.

Budynas, R. G. & Nisbett, J. k. (2008). *Diseño en Ingeniería Mecánica de Shigley*. McGrawHill.

Cho, K. & Gent, A. N. (1985). An improved torsional method for determining the fracture toughness of stiff materials and of adhesive joints. International. *J. Fracture,* 239-244.

Ciccotti, M., Gonzato, G. & Mulargia, F. (2000). The double torsion loading configuration for fracture propagation: an improved methodology for the load-relaxation at constant displacement. *International J. Rock Mech. & Min. Scie.* 37: 1103-1113.

Collins, J. A. (2003). *Mechanical Design of Machine Elements and Machines*. Jhon Wiley and Sons.

Evans, A. G. (1972). A method for evaluating the time-dependent failure characteristics of britte materials - and its application to polycristalline alumina. *J. Mat. Scie.,* 7 (10), 1137-1146.

Gerry, D. J. & Outwater, J. O. (1969). On the fracture energy, rehearing velocity and refracture energy of cast epoxy resin. *J. Adhesion,* 1:290 298.

Holder, J., Olson, J. E. & Zeno, P. (2001). Experimental determination of subcritical crack growth.*Geophysical Research Letters*, 28 (4), 599-602.

Kies J. A. & Clark A. B. J. (1969). Fracture propagation rates and times to fail proof stresses in bulk glass. *Proceedings of the Second International Conference on Fracture*; 483-491.

Nara, Y. (2006). Subcritical Crack Growth in Rock, *Int. J. Rock Mech. Min. Scie.* 43 (3), 437-453.

Outwater, J. O. & Gerry, D. J. (1966). *On the fracture energy of glass NRL Interim Contract Report*.University of Vermont, Burlington.

Park, N. (2006). Discrete Element Modeling of Rock Fracture Behavior: Fracture Toughness and Time-Dependent Fracture Growth, *Dissertation by Doctor Philosophy.* The University of Texas, Austin, U.S.A. 291pp.

Saadaouia, M., Reynauda, P., Fantozzi, G., Peronnet, F. & Caspar, P. (2000). Slow crack growth study of plaster using the double torsion method. *Ceramics International,* 26 (4), 435-439.

Sun, Z. & Ouchterlony, F. (1986). Fracture toughness of stripa granite cores. International *J. Rock Mech. Min. Scie. & Geom. Abstracts,* 23 (6), 399-409.

Whittaker BN, S. R. (1992). *Rock Fracture Mechanics - Principles, Design and Applications.* New York: Elsevier Science, 90-107.

Williams, D. P. & Evans, A. G. (1973). A simple method for studying slow crack growth. *J. Test Eval.*, 1 (4), 264-270.