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Fracture Toughness Analysis of Ankara Andésite

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ABSTRACT: Fracture toughness, which is the resistance offered by a rock material against crack propagation is a material property used in the design of rock drilling equipment, rock bursting, hydraulic fracturing, wellbore stability and stability of jointed rock masses. Hollow Brazilian cylindrical core specimens were used in order to study mode-l fracture toughness behavior Ankara andésite. The load-displacement curves under diametrical compression were recorded and analysed for different crack propagation stages under mode-l loading. Different specimen geometries and crack initiation and propagation stages are investigated by numerical modeling using a boundary element program TDLCR, a finite element fracture analysis code FRANC 2D/L and a large deformation finite difference program FLAC. Comparison of the results of different numerical modeling techniques is provided in this work.

I INTRODUCTION

Fracture will always have a wide- ranging importance to scienti.sts. In solving great many engineering problems, understanding the mechanics and mechanisms of rock fracture is a key element.

Fracture mechanics is primarily used to prevent and predict catastrophic failure of structures of man-made materials such as metals, plastics, and ceramics. Before the development and integration of fracture mechanics into the conventional design procedures, strength of materials approach was the only major design tool in which the stress in a structure is compared with some material strength value in order to decide whether failure will occur or not.

With the exception of a few early investigations, rock fracture mechanics is a rather recent field study. Griffith (1921) was the first to make a quantitative connection between strength and crack si/e. Based on his analysis Griffith found that two necessary and sufficient conditions arc required for a crack growth. First, sufficient stress must be provided at the crack tip to produce a crack growth mechanism. Second, sufficient energy must flow to the crack tip to supply the necessary work done for the creation of new surfaces at the tip.

Until the late 1940s, Griffith's pioneering work (1921-1924) was not seen as having much relevance to engineering. Irwin (1957) modified the original Griffith's fracture theory and postulated surface energy characteristics of fracture, which is measurable in a fracture test, and he introduced the concept of stress intensity factor.

Irwin observed that there are three independent kinematic movements of the upper and lower crack surfaces with respect to each other, K, for the opening mode, K_M for the shear mode and Km for the tearing mode.

In present day elastic fracture mechanics, the governing parameter is the stress intensity factor K, at least in the linear case. It is, on one hand, a measure of the singularity *of* the stress field at a loaded crack tip and, on the other, intimately related to the available energy release rate (Irwin 1957).

The basic relation equates K to a critical value, which is often taken as a material property, and called the plane strain fracture toughness, K_{lc}. As a short definition, fracture toughness indicates the ability of rock to resist crack propagation and it is the fracture energy consumption rate required to create new surfaces. Stress intensity factor is usually determined by numerical analysis and its dimensions are, stress x $\sqrt{\text{(crack length)}}$, i.e Pa x $\sqrt{m}$ or $\frac{N}{m^{1.5}}$.

Fracture toughness value is used as a parameter for classification of rock material, an index of fragmentation processes such as tunnel boring and model scale blasting and a material property in the modelling of rock fragmentation like rock cutting, hydraulic fracturing, gas driven fracturing, explosive stimulation of gas wells, radial explosive fracturing and crater blasting as well as in stability analysis and m the interpretation of geological teatures (Sun 1986). The use of fracture toughness is also common in the design of rock drilling equipment and in the prediction of rock drilling forces (Krishnan 1998).

A wide variety of testing methods and specimens has been used for assessing fracture toughness of locks. Several researchers have adopted ISRM "Suggested methods for determining the fracture toughness of rock", i.e. Chong et al.(1987). Şantay (1990), Lim et al. (1993), Kruppu (1997), Chang et al. (2002). In this study Modified Ring Test, developed by Thiercelin el al. (1986), was used for determining the fracture toughness value of Ankara andésite.

2 TESTING METHOD

2. / *Rock Sample and Specimen Description*

Ankara andésite blocks were obtained from a quarry near Gölbaşı region located 20 km south of Ankara. General mechanical properties of this andésite were determined fust before the fracture testing and these results are summarized in Table 1.

Table I Mechanical properties of Ankara andésite

Uniaxial compressive strength	63.81 MPa
Young modulus	19.85 GPa
Indirect tensile strength	6.71 MPa
Poisson's ratio	0.146

2.2 *Testing Apparatus*

MTS 815 servo controlled hydraulic testing machine in Mining Engineering Department of Middle East Technical University was used as the loading system.

To measure the displacement in our experiments LVDT responding to the stroke movements of the actuator was used. Here the stroke LVDT capacity is ± 50 mm with ± 0.01 mm accuracy. An external 500 kN load cell with ± 0.25 kN error band was used to measure the load. Loading rate in the testing was around 0.0005 mm/sec.

2.3 Modified Ring Test

Modified Ring test is essentially based on hollow cylinder geometry with two diametrically opposed, flat-loading surfaces as shown in Figure 1.

In this study, andésite blocks were prepared by using two different drill bits. One has 75 mm and the other one has 150 mm diameter. For these specimens 5 mm and 18.5 mm hole radii were used, respectively.

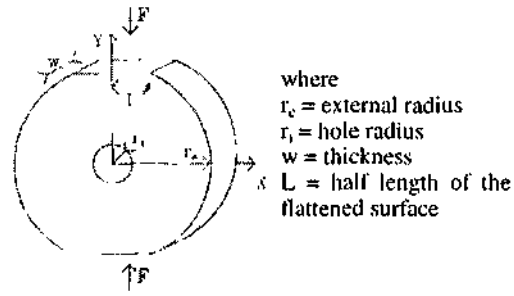

Figure I Modified Ring lest specimen geometry 1986)

The specimen is compressed across its diameter by applying a uniform displacement at constant rate. As the tangential stress exceeds the tensile strength a crack is initiated at Ihe lop and bottom of the hole and this crack propagates vertically towards the loaded ends with increasing load. During the propagation of the crack K, changes with increasing crack length. No analytical solution is available to find this change. However, numerical modelling can generate the stress intensity factor as a function of the crack length.

3 NUMERICAL MODELING

The Modified Ring test for plane strain fracture toughness determination involves two phases: i) generation of laboratory load-deformation record of a specimen, and ii) numerical computation of crack-tip stress intensity factors in a model with exactly the same dimensions as the laboratory specimen (Thiercelin 1986). In this study, boundary element program TDLCR, finite element code FRANC2D/L, and finite difference program FLAC were used for modeling, analyzing, and comparing the tests numerically.

Two Dimensional Linear Crack (TDLCR) boundary element program is a displacement discontinuity type boundary element method with a main program and three subroutines. For the first crack initiation analysis, tangential stress at the top and bottom boundary of the hole is checked by comparing it to the tensile strength. When $a_e > T_n$, a small crack with displacement discontinuity (DD) elements and one crack tip element are added to the top and bottom of the hole parallel to the applied loading. And this procedure is repeated by increasing the length of the crack along the loading axis to simulate the crack propagation. By this way,variation of stress intensity factor with increasing crack length is determined.

FRANC2D/L developed by Paul Wawrzynek at Cornell University (FRANC2D/L Catalog 1997) is an interactive program for the two-dimensional analysis of structures. Its capabilities include elastic and elastic-plastic material response, simulation of linear elastic (LEFM) and elastic-plastic crack growth, analysis of layered structures, and a linear plate bending option.

Fast Lagrangian Analysis of Continua (FLAC) is a finite difference program and it is primarily used for geotechnical engineering applications, the code includes special numerical representations for the mechanical response of geologic materials.

4 RESULTS AND DISCUSSION

A typical load-displacement curve for the Modified Ring test is shown in Figure 2.

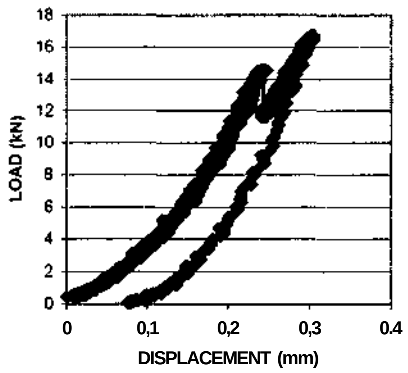

Figure 2 Load-displacement record of MTS 815 for 75 mm specimen

It is known from the experimental work and previous work by Thiercelin (1986) that once the crack is initiated it grows very fast in an unstable manner to a critical length where a = aL.

At this point a load drop is to be observed in the load-displacement behaviour. After this critical length crack continues to propagate in a stable manner, since the crack front approaches and enters into the confined zone or high stress gradient zone of the compressive stress field under the loaded ends. This behaviour which is reflected as a drop in the load-displacement record in Figure 2 appears as a peak in the numerically generated K_t - a record of Figure 3.

Results of boundary element modeling of crack propagation using the displacement discontinuity

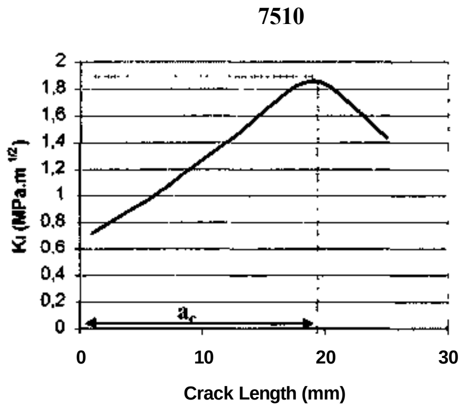

Figure 3 Variation of SIF with crack length during crack propagation

elements are presented in Table 2. K*] shows the normalized stress intensity factor where

$$K_I^* = \frac{K_{I\,max}\pi r_i}{F_C\sqrt{(a_i + r_i)\pi}} \quad (1)$$

is dimensionless. This normalization is done for an easy comparison of stress intensity factor to the stress intensity factor of a tensile crack of length (a + r,) under tension *a* where the stress intensity factor is o(a + r,)$^{1/2}$. a_c corresponds to the critical stress value at the point of first load drop and a, corresponds to the critical crack length at this drop. Stress intensity factor is K, nux at this stage.

Table 2 Results of numerical modeling of crack propagation by boundary element method

r_i/r_e (α)	a_C (mm)	σ_C (MPa)	$K_{I,max}$ (MPa.m$^{1/2}$)	K_I*
		7510		
0.133	25	52.7	2.26	2.06
0.133	22	39.94	2.04	1.723
0.133	20.5	33.54	1.87	1.451
0.133	19	30.4	1.71	1.21
0.133	14.5	25.87	1.31	0.804
		15037		
0.247	41.5	22.76	1.92	2.86
0.247	38.5	17.59	1.76	2.33
0.247	32.5	15	1.68	2.06
0.247	26.5	12.91	1.52	1.8
0.247	23.5	10	1.07	1.19

For a general comparison, the results of numerical modeling by TDLCR boundary element method and FLAC analysis are shown in Figure 4 for 75 mm diameter and for 150 mm diameter specimens.

Displacement Discontinuity model result was closer to the experimentally measured result. For small 75 mm specimens. DD result deviate about 9 % from the mean experimental value whereas FLAC model deviation is 17 %. This deviation is reduced down to 6 % for DD modeling and 9 % for FLAC modeling for large size specimens that are 150 mm in diameter. In this figure internal hole radius r, changes between 5 mm and 18.5 mm in order to obtain different r/r_c ratios for 75 and 150 mm specimens.

For computation of K_{IC} values following formula (Fischer, 1996) was used:

$$K_{IC} = (\sigma_c)_{lab} \left(\frac{K_{I\,max}}{\sigma_c} \right)_{model} \quad (2)$$

This expression serves as to scale the numerical values by the experimental results.

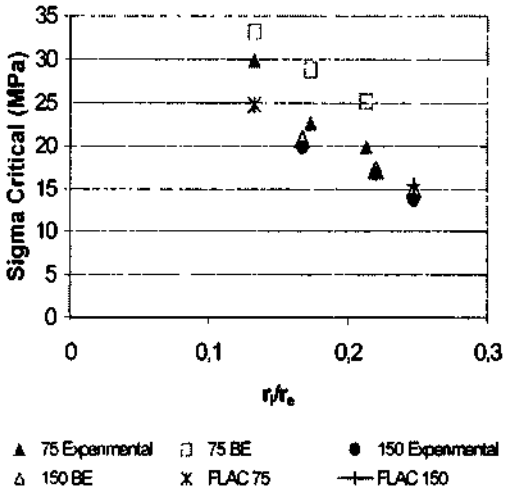

Figure 4 Comparison of OY vs r_i/r_c results from experiments and numerical models

$K|_r$ values calculated this way are compared to $K|_{nm}$ values of boundary element modeling in Table 3.

Table 3 Comparison of Ki. „u\ and KK

	$K_{I,max}$ (Boundary Element) $MPa\sqrt{m}$	K_{IC} $MPa\sqrt{m}$
7510	1.853	1.67
15037	1.678	1.535

5 CONCLUSIONS

Fracture toughness study of Ankara andésite was carried out by using hollow Brazilian cylindrical core specimens. This study involved into two parts; i) experimental work, ii) numerical analysis.

Modified Ring test using hollow Brazilian discs with flattened loading ends is a convenient test for the determination of mode-1 fracture toughness K_{Ic}. Specimens are quite easily prepared from the rock cores of different diameters. Test procedure is simple and quick, and the load-displacement results are easy to interpret provided that a displacement controlled loading system is available such as the MTS 815 servohydraulic testing system used here.

Critical load values obtained from numerical modeling were quite close to the experimentally observed ones, especially for DD boundary element modeling being within 6-9%, FLAC models results were within 10-15% of the experimental averages. Numerical modeling predictions were better for larger size specimens for both modeling techniques.

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