Stability Assessment of Underground Openings in British Rocks using Fracture Toughness as Failure Criterion

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ABSTRACT

The research work presented in this paper can be divided into two phases. The first phase is concerned with laboratory work to evaluate the fracture toughness of some rocks encountered in the British mines. Phase two is concerned with computer modeling to investigate the application of fracture toughness in the design of rock structures.

Fracture toughness of some rocks was determined using Single Edged Cracked Round Bar in Bending (SECRBB) technique. Compliance calibration technique was used to determine the true crack length at failure in opening mode.

In order to apply the fracture toughness results in the design of rock structures, the boundary element computer program for two dimensional stress, displacement analysis in homogeneous media under uniform or gravitational loading was used to calculate the stress concentration at the crack tip. Subsequently these stress concentration values were used to determine the fracture toughness. Fracture toughness results obtained under laboratory conditions were used as failure limit and compared with calculated values obtained from stress concentrations at the crack tip. This is based on the premise that due to high stress concentration near the crack tip, the fracture will initiate and propagate when the value of fracture toughness reaches a critical level. Hence, the extent of tensile fracture could be predicted around the mine opening.

Keywords: Fracture toughness, tensile mode failure, boundary element method.

1. INTRODUCTION

Fracture toughness is a fundamental property of rock which governs the growth of fractures within the rock under static or dynamic stresses (Kahrama & Altindag, 2004 and Nasseri et al., 2005). The role of fracture mechanics in the design of rock structures, such as underground openings of various types, surface mine slopes, foundation of bridges and dams and rock fragmentation is vitally important. However, because of the complexities of rock structures and lack of understanding of fundamentals of the failure mechanism, it has become customary to use the engineering approach in the design of stable rock structures (Hardy, 1973). Considerable attention has been given in the recent past to the study of rock fracture and attempts are being made to apply the fracture mechanics approach to the design of safe mining structures.

In mining engineering the fracture mechanics may be applied to calculate the formation of fracture zones around mine openings, thus estimating support requirements and formulating guidelines for the selection of mine roadway support system (Singh & Pathan, 1986).

The aim of this research work is twofold, first to evaluate fracture toughness of some British rocks such as Ryefield sandstone, siltstone, basalt and granite and second to apply the fracture toughness as a failure criterion in the design of underground mine openings using numerical technique.

2. DETERMINATION OF FRACTURE TOUGHNESS OF BRITISH ROCKS

Fracture toughness of Ryefield sandstone, siltstone, basalt and granite was determined using Single Edge Cracked Round Bar in Bending (SECRBB) technique. Experimental set-up for three point bending test under Howden-2000 servo-hydraulic stiff testing machine is shown in Fig.1. Fracture toughness was calculated using the following equation (Bush, 1977 and Ouchterlony, 1979):

$$K_I = 8.Y.F.L.\sqrt{a} / \pi D^3 \qquad (1)$$

Where

K_I = fracture toughness ($MN/m^{3/2}$),

Y = dimensionless stress intensity factor,

F = experimentally observed failure load (MN),

a = crack length at failure (m),

D = specimen diameter (m),

L = specimen span length (m), and

L = 3.33 D.

The formula for dimensionless stress intensity factor 'Y' is given as follows:

$$Y = 1.252 [1+19.646(a/D)^{4.5}]^{0.5} / [1-a/D]^{0.25} \qquad (2)$$

Where
a = crack length at failure, and
D = diameter of the specimen.

Compliance calibration technique was used to determine the crack length at failure. Following best fit equations were found for compliance calibration graphs as shown in Figs. 2, 3, 4 and 5.

For Ryefield sandstone:

$$\lambda = 6.022 + 63.38(a_o/D)^{1.6} \tag{3}$$

For siltstone:

$$\lambda = 5.707 + 46.28(a_o/D)^{3} \tag{4}$$

For basalt

$$\lambda = 1.06 + 112.41(a_o/D)^{4.3} \tag{5}$$

For granite

$$\lambda = 1.19 + 57.42(a_o/D)^{2.9} \tag{6}$$

Above Eqs. (3 – 6) were used to determine the crack length 'a' at failure knowing the compliance at failure. Subsequently, fracture toughness results of Ryefield sandstone, siltstone, basalt and granite were calculated using Eqs. 1 & 2. Average values of fracture toughness of these rocks are given below:

For Ryefield sandstone

$$K_I = 1.064 \pm 0.178 \ \text{MN/m}^{3/2}$$

For siltstone

$$K_I = 0.94 \pm 0.07 \ \text{MN/m}^{3/2}$$

For basalt

$$K_I = 1.99 \pm 0.12 \ \text{MN/m}^{3/2}$$

For granite

$$K_I = 2.07 \pm 0.29 \ \text{MN/m}^{3/2}$$

3. PREDICTION OF FAILURE AROUND MINE OPENINGS USING NUMERICAL TECHNIQUE

A Boundary Element Program for two dimensional stress, displacement analysis (in homogeneous isotropic media under uniform or gravitational loading) was used to predict the tensile mode failure in the crown of an underground excavation. A vertical crack was simulated in the crown of an opening and stress concentration at the crack tip was determined using Boundary Element Program and the fracture toughness parameter was evaluated using the following relation (Ewalds & Wanhill, 1984).

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \mathrm{Cos}(\theta/2)\left[1 - \mathrm{Sin}(\theta/2)\,\mathrm{Sin}(3\theta/2)\right] - \frac{K_I}{\sqrt{2\pi r}}\left[P/2r\right]\mathrm{Cos}(3\theta/2)$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \mathrm{Cos}(\theta/2)\left[1 + \mathrm{Sin}(\theta/2)\,\mathrm{Sin}(3\theta/2)\right] + \frac{K_I}{\sqrt{2\pi r}}\left[P/2r\right]\mathrm{Cos}(3\theta/2) \qquad (7)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \mathrm{Sin}(\theta/2)\,\mathrm{Cos}(\theta/2)\,\mathrm{Sin}(3\theta/2) - \frac{K_I}{\sqrt{2\pi r}}\left[P/2r\right]\mathrm{Sin}(3\theta/2)$$

Where

σ_x = Normal stress component in X-direction (MN/m^2),
σ_y = Normal stress component in Y-direction (MN/m^2)
τ_{xy} = Shear stress component in X-Y plane (MN/m^2),
K_I = Fracture toughness in opening mode (MN/$m^{3/2}$),
r, θ = Polar coordinates of the point of stress concentration around crack tip (m, deg.), and
P = Width of crack (m).

In above set of equations, K_I describes the fracture toughness parameter. If the calculated value of K_I from Eq. 7 is greater than the value of K_I determined from laboratory tests, then the crack will initiate and propagate in its plane.

3.1 Prediction of Tensile Failure in Ryefield Sandstone

A rectangular opening with a cross-sectional area of 5m x 3m was analyzed to predict the tensile failure at different depths between 100m – 400m. A 2mm wide crack was simulated in the roof of the opening, the crack length ranges from 2mm to 1.0m. The boundary element computer program was run in order to evaluate stress concentration around the crack at different grid positions. Various grid positions (GRID 0, 1, 2, 3, …) show the distance between the tip of the simulated crack and the point of stress concentration around the crack tip. The distance between two consecutive grids is 2 cm. Normal distance between the first grid line and the surface of the excavation is kept constant as DELN=0.02m for all depths. The fracture toughness values were calculated from stress concentrations using Eq. 7 and are plotted against crack length as shown in Figs. 6, 7 and 8 for the depths of 200m, 300m and 400m respectively. The critical value of fracture toughness of Ryefield sandstone was determined as 1.06 ± 0.178 MN/$m^{3/2}$ and is used as a failure limit as shown in Figs. 6, 7 and 8. It is clear from the Fig. 6 that all the curves are well below the failure limit, so it can be concluded that the rectangular excavation in Ryefield sandstone is safe at the depth of 200m as far as tensile failure is concerned. In Fig. 7 curve ‘1’ is just touching the failure limit at a= 1.0 m. Therefore, it may be concluded that tensile fracture can extend up to 2 cm when 1.0 m crack is introduced in the opening at the depth of 300 m. It can be revealed from the Fig. 8 that a crack is propagated 4 cm ahead. Tensile fracture occurred around the mine opening at different depths is presented in Figure 9. A linear relationship was found between tensile fracture and depth below surface.

3.2 Prediction of Tensile Failure in Siltstone

The same excavation was analyzed to determine the tensile fracture in siltstone as considered in previous case. Fracture toughness values were calculated from stress concentration around the simulated crack. The effect of crack length on fracture toughness has been presented in Figs. 10, 11 & 12 for the depths of 200m, 300m and 400m. Increasing trend of fracture toughness with respect to crack length was found. The critical value of fracture toughness for siltstone is 0.94 ± 0.07 $MN/m^{3/2}$ which is shown as failure limit in these Figures. In Fig. 10 curve '0' partially crosses the failure limit that means fracture has been initiated in the vicinity of the crack tip but not propagated yet. Curve '1' crosses the failure limit when $a = 0.8$ m (Fig. 11), thus it can be concluded that tensile failure is extended up to 2 cm ahead of the crack in siltstone at a depth of 300 m. It is obvious from the Fig. 12 that the crack is propagated up to grid No. 2 when $a = 1.0$ m which shows that tensile crack has been propagated up to 4 cm. The effect of depth below surface on tensile failure is shown in Fig. 13.

3.3 Prediction of Tensile Failure in Basalt

Fracture toughness values were calculated from stress concentration around the simulated crack in basalt. Crack dimensions were same as used before. Fracture toughness results are presented against crack length in Figs. 14, 15 and 16 for the depths of 200m, 300m and 400m respectively, in order to predict the tensile failure in basalt. The critical value of fracture toughness for basalt is 1.99 ± 0.12 $MN/m^{3/2}$ which is used as failure limit. It is clear from Figs. 14, 15 and 16 that curve '0' crosses the failure limit partially, which shows the crack initiation around the simulated crack, but there is no crack propagation in basalt at all depths of 200 m – 400 m.

3.4 Prediction of Tensile Failure in Granite

A rectangular opening (5m x 3m) was analyzed at four different depths below surface to predict tensile failure in granite by using the fracture toughness as a failure criterion. Fracture toughness values were calculated from stress concentration around the simulated crack. Fracture toughness results are plotted against crack length in Fig. 17 at the depth of 400m, to determine the extent of tensile failure. The critical value of fracture toughness for granite is 2.07 ± 0.29 $MN/m^{3/2}$ which is used as a failure limit. In Fig. 17 curve '0' crosses the failure limit when crack length is approaching 1 m. Therefore, it can be concluded that the rectangular opening of given dimensions is quite safe at a depth of 400 m below surface.

4. CONCLUSIONS

- Boundary Element Computer Program was used to calculate the stress concentration near the crack tip, subsequently, fracture toughness was determined from stress concentration. Results have shown that due to high stress level near the crack tip, fracture will initiate and propagate when the value of fracture toughness reaches a critical level.

- Fracture toughness can be used as inherent material property of rock to predict the extent of fracture zone in the crown of underground excavation.
- Rectangular excavations (5m X 3m) in Ryefield sandstone and siltstone are safe at the depth of 200m.
- Rectangular opening (5m x 3m) in basalt and granite are safe at the depths of 400m.

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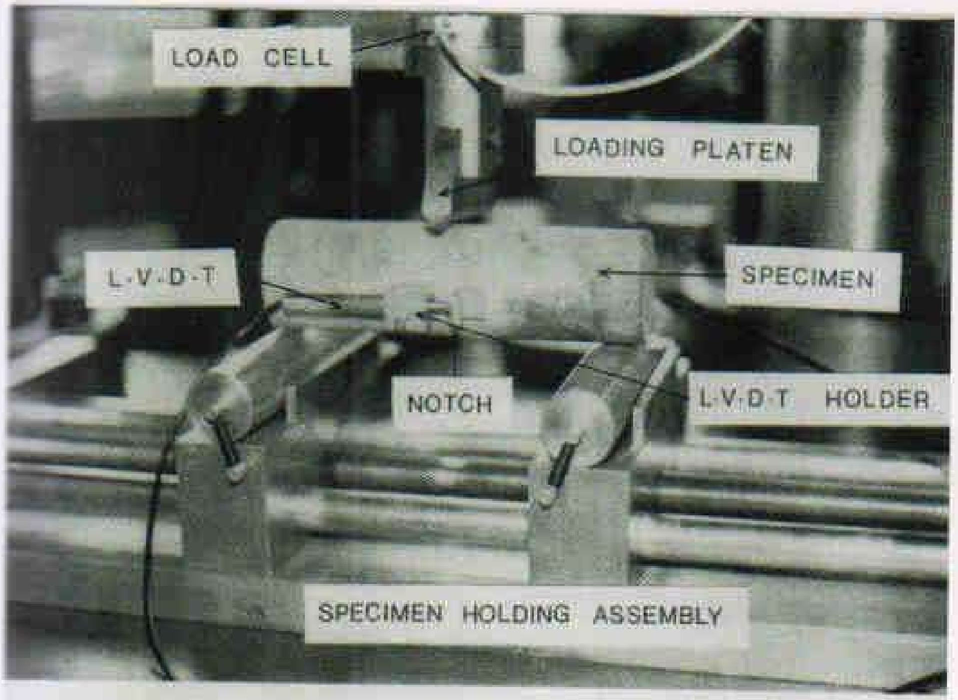

Figure 1: Experimental Set-Up for Three Point Bending Test Under Howden-2000, Stiff Press.

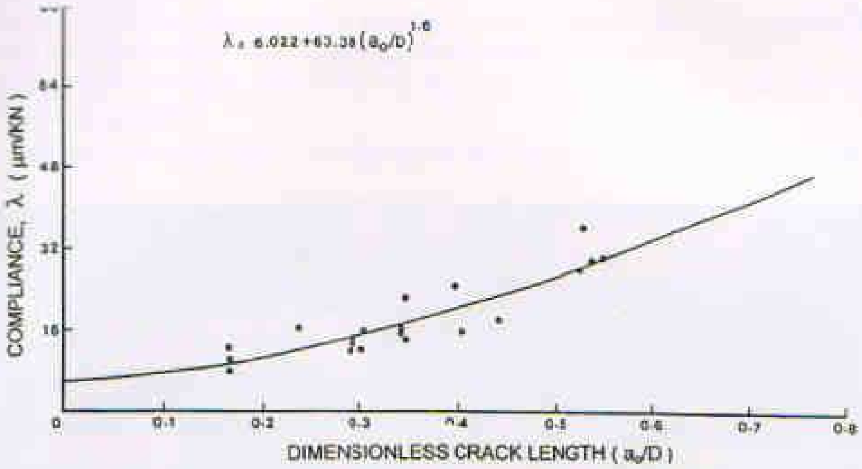

FIGURE 2 Compliance Calibration Graph of Ryefield Sandstone for the Determination of Crack Length.

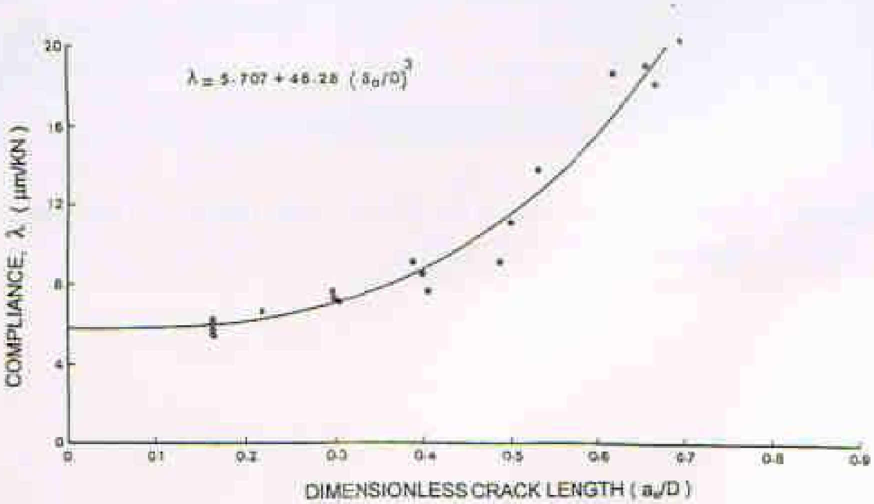

FIGURE 3 Compliance Calibration Graph of Siltstone for the Determination of Crack Length.

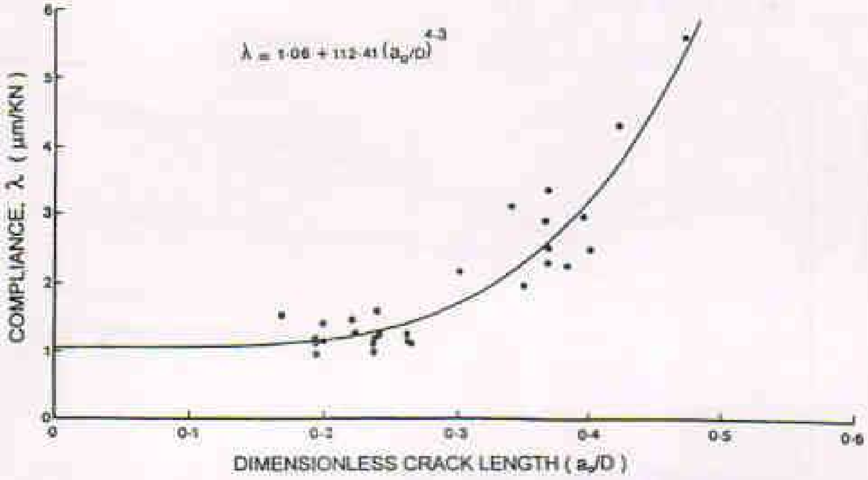

FIGURE 4 Compliance Calibration Graph of Basalt for the Determination of Crack Length.

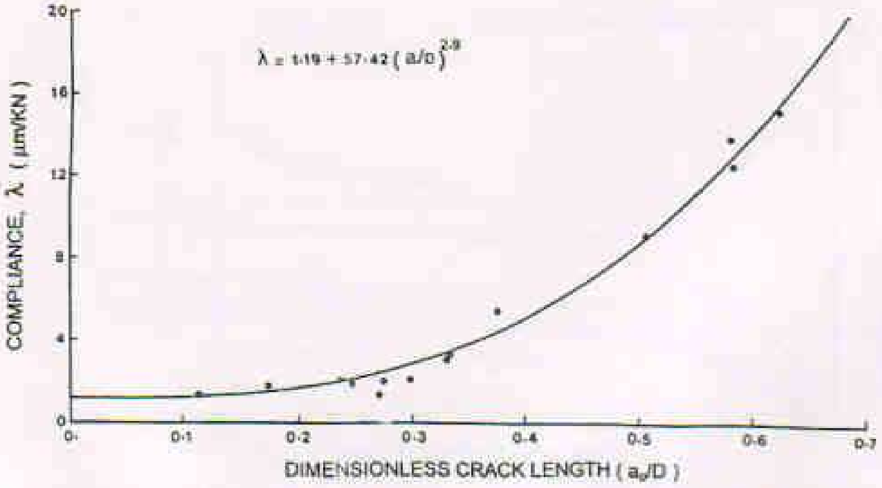

FIGURE 5 Compliance Calibration Graph of Granite for the Determination of Crack Length.

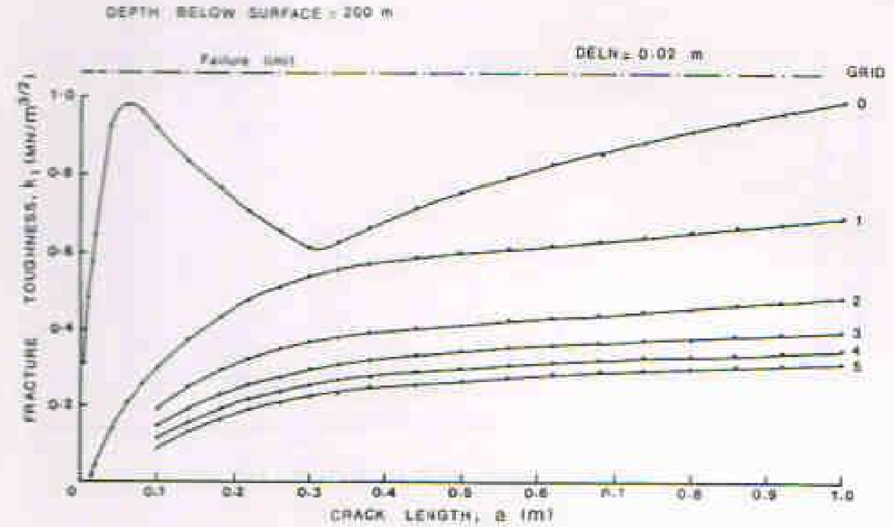

FIGURE 6 Determination of Tensile Failure in Ryefield Sandstone at the Depth of 200m Below Surface.

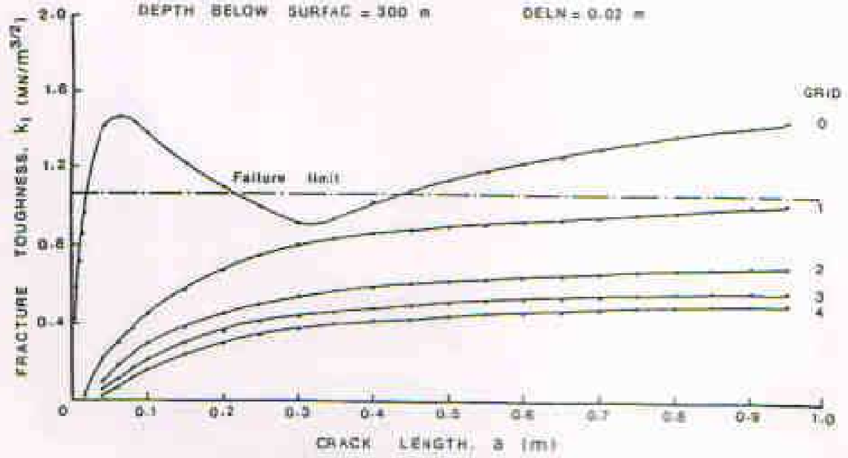

FIGURE 7 Determination of Tensile Failure in Ryefield Sandstone at the Depth of 300m Below Surface.

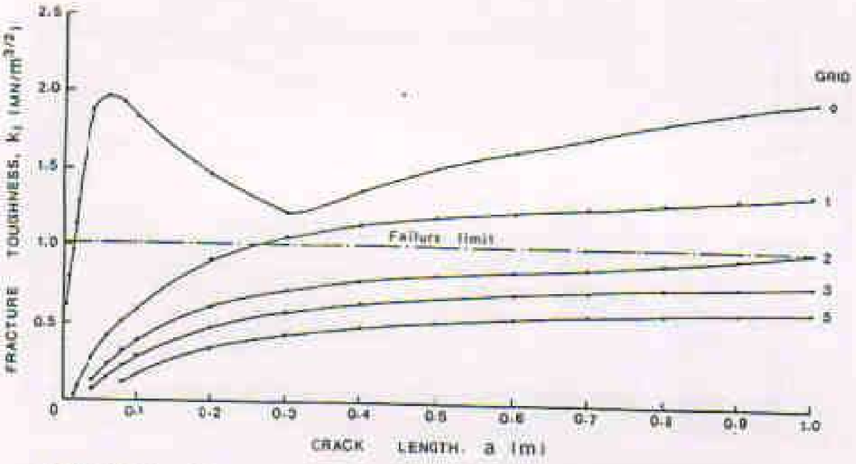

FIGURE 8 Determination of Tensile Failure in Ryefield Sandstone at the Depth of 400m Below Surface.

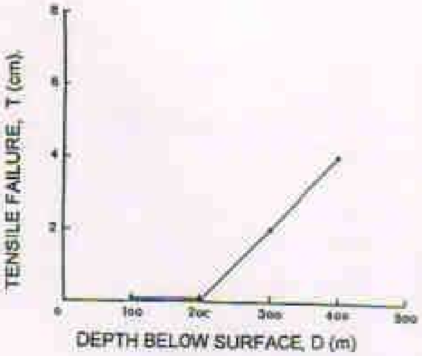

FIGURE 9 Effect of Depth Below Surface on Tensile Failure in Ryefield Sandstone.

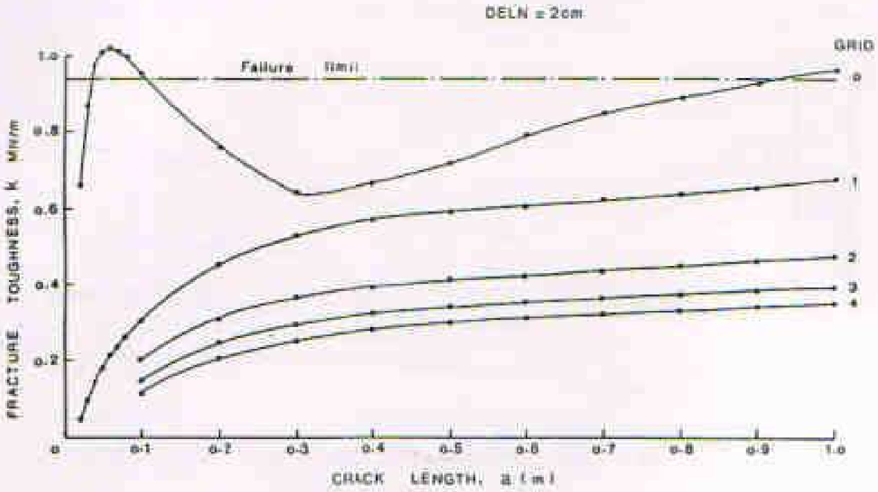

FIGURE 10 Determination of Tensile Failure in Siltstone at the Depth of 200m Below Surface.

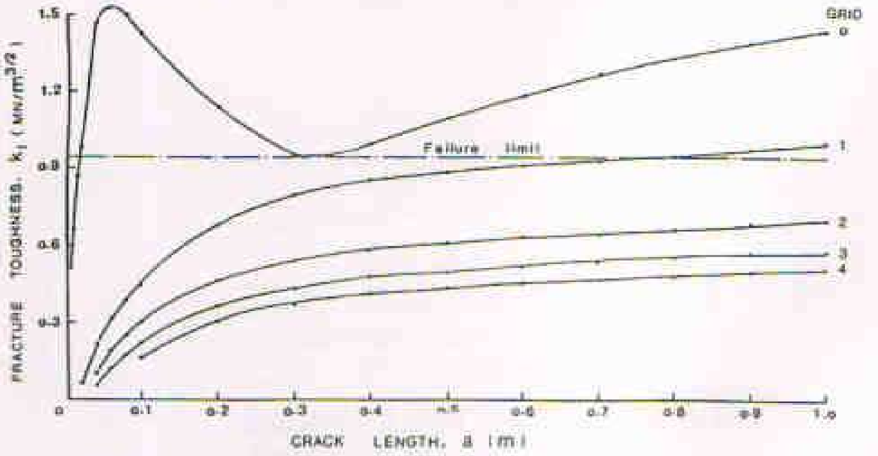

FIGURE 11 Determination of Tensile Failure in Siltstone at the Depth of 300m Below Surface.

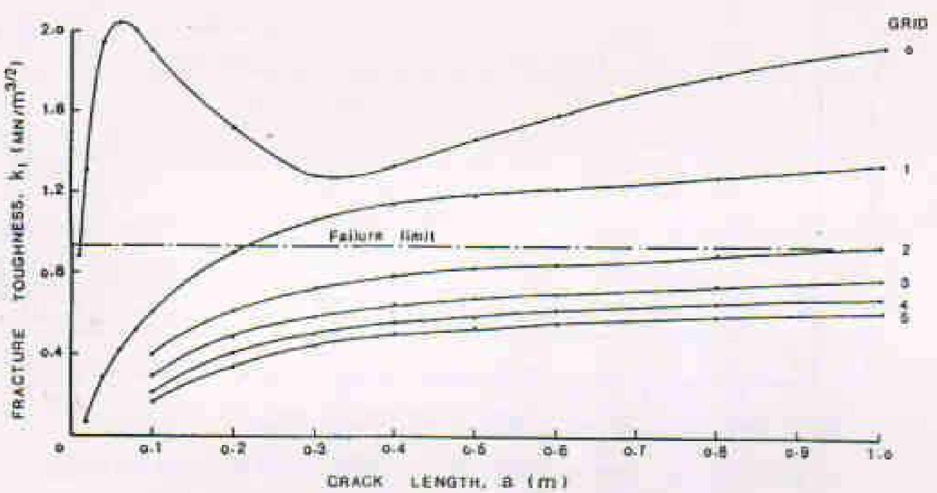

FIGURE 12 Determination of Tensile Failure in Siltstone at the Depth of 400m Below Surface.

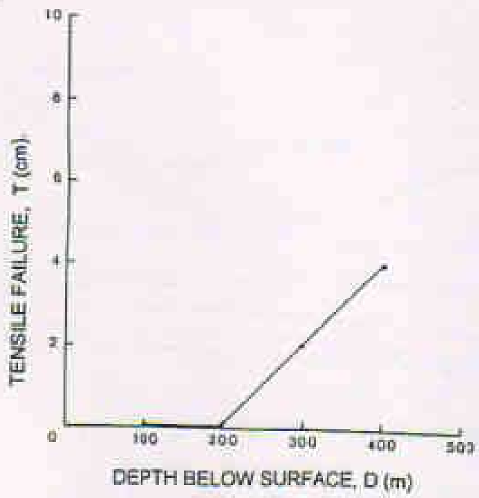

FIGURE 13 Effect of Depth Below Surface on Tensile failure in Siltstone

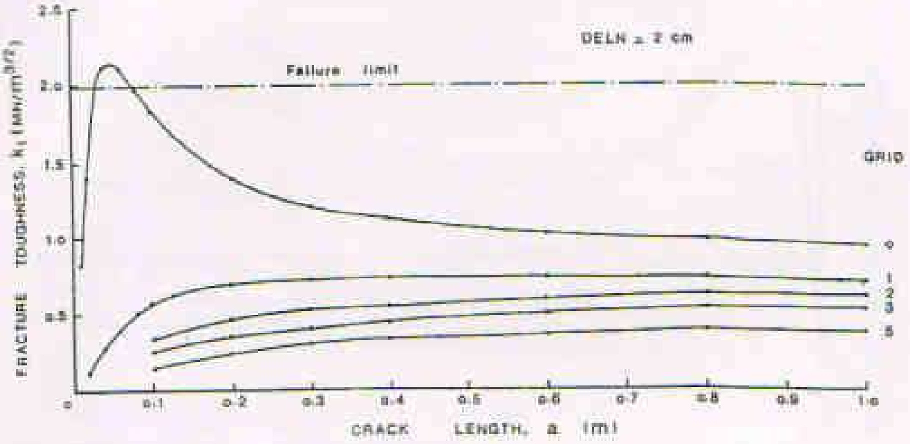

FIGURE 14 Determination of Tensile Failure in Basalt at the Depth of 200m Below Surface.

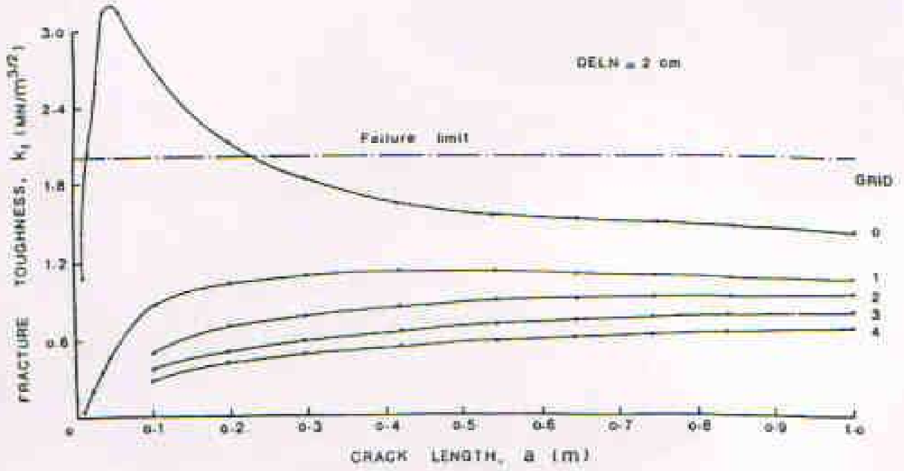

FIGURE 15 Determination of Tensile Failure in Basalt at the Depth of 300m Below Surface.

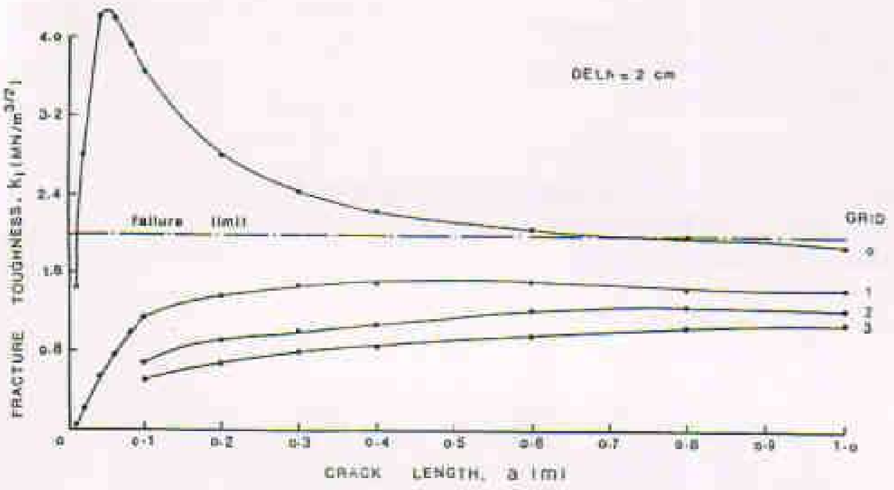

FIGURE 16 Determination of Tensile Failure in Basalt at the Depth of 400m Below Surface.

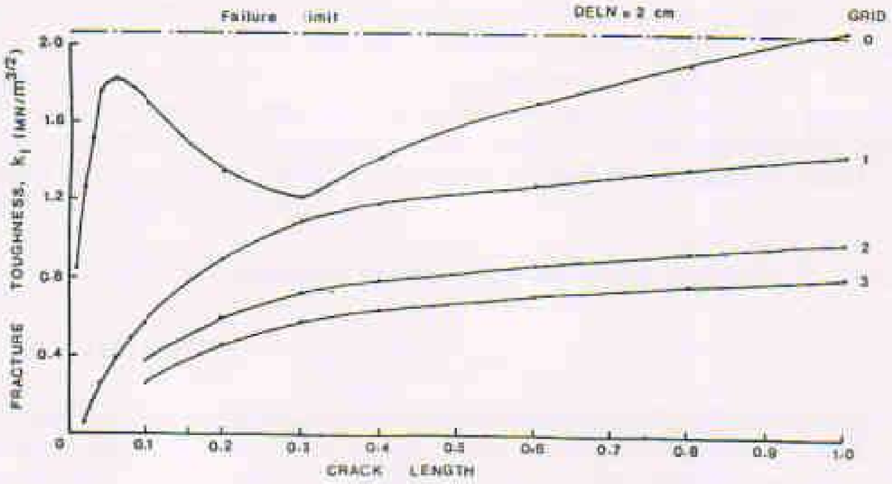

FIGURE 17 Determination of Tensile Failure in Granite at the Depth of 400m Below Surface