APPROPRIATE FRACTURE MECHANICS SPECIMENS FOR TESTING ROCKS

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Two kinds of rocks: andesite tuff and compact limestone have been investigated. In addition to the conventional TPB tests, disc-shaped specimens modified for the special requirements of rocks have been applied too. The small modification in the arrangement of loading elements had the consequence of a great difference in the interpretation of the results. Photoelastic experiments were therefore necessary to evaluate new formulas for the calculations.

INTRODUCTION

The fracture mechanics concept is used for the present in very different fields of techniques and to very different kinds of materials. Most frequently it is used, of course, to metals, but ceramics, plastics, concrete and rocks are also subjects to fracture mechanics tests, because it has been recognized that cracks and defects are present in every material and their effect is detrimental.

For fracture mechanics tests a few kinds of specimens are widely used, those which proved to be the most advantageous of many possible shapes. The viewpoints for selecting an appropriate specimen form can be the amount of material necessary, the force needed to the test /capacity of testing machine/, an easy way for instrumentation, simple and low cost methods for machining

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and many others. Because metals were the first materials to be involved, the conventional shapes of specimens have been evaluated in respect of metals. Later, in many investigations performed on other materials the conventional types of specimens were used, probably more as a matter of routine, than for other reasons. So, for example, four-point bend specimens were used by Ziegeldorf et al. /1/ to concrete, by Lewis and Smith /2/ to Si-Al-O-N ceramics and by Myers and Hillberry /3/ to monocrystalline silicon. Carpinteri /4/ applied TPB specimens to investigate marble and other materials.

The application of traditional specimen shapes offers, of course, some advantages. Usual formulas and computer programs may be used for the calculations. The comparison of data with other results is perhaps more realistic if the measurements have been performed by the same method. But the disadvantages may balance or even overbalance the profit. This refers especially to a field where only few experiences and accumulated data exist for the present, but where the importance of fracture mechanics will certainly increase in the near future. It seems therefore reasonable to search for more appropriate specimen shapes, as it is done e.g. in the work of Szendi-Horváth /4/.

PRELIMINARY EXPERIMENTS

Two kinds of rocks: andesite tuff and compact limestone had to be investigated, among others the fracture mechanics parameters. At first, mainly for comparison, TPB specimens of regular shape with different dimensions have been machined, according to Fig.1. But the machining of parallelepipeds of exact dimensions was rather difficult with the equipment of the Laboratory of the Department of Mineralogy and Geology. The usual way for testing rocks starts with a crown drill, that is, with a hollow drill, which produces cylindrical rods of the rock to be examined. To cut these rods to parallelepipeds means a lot of work and a lot of wasted material. Therefore we made an effort to find a better specimen shape and chose the one recommended by Erismann and Prodan /6/ /see Fig.2/. This is a special kind of disc which is easy to prepare from a cylindrical rod.

Another problem related with the three- or four-point bend tests is the transmission of the load. This is accomplished by rolls which contact the specimens on a line. But rocks are far brittler than metals and far less able to be deformed. So the transmission of the load on a line raises very high local stresses and may produce local damage. Even worse, in a real case, load distribution is hardly uniform along the line. As it can be seen in Fig. 3 /overdone/ the lack of parallelity of the axes of the rolls or the imperfect machining of the specimens equally lead to a decrease of the contact area, so to an increase of stress concentration and finally to a premature fracture.

The same problem exists also with the specimen given in reference /6/, since the load is passed by rolls too. Therefore we slightly modified the arrangement of the test supposing that a small modification does not alter the circumstances and the formulas and factors given by the authors will remain valid for the calculations. The modified arrangement of the test is given in Fig.4. The plane + curved cut-out has been altered to only plane surfaces and instead of rolls two prisms have been applied to ensure uniform load distribution on a finite surface.

Both the TPB and disc specimens were notched only, because it was supposed that the many small cracks within the rock will serve as crack starter without an artificial fatigue crack. This reduced labour demand radically.

The tests were performed on an Instron TTDM machine at a crosshead speed of 1 mm/min. Critical stress intensity factors were calculated with the formulas given in ASTM E399-72 and in reference /6/, resp., which yielded the results summarized in Table 1.

It can be seen that these results are not satisfactory, because the deviations due to the sort of specimens or to the dimensions of the discs are far too great and cannot be explained. Therefore the circumstances of the tests and the calculating methods were carefully revised and it was concluded that the formula given in reference /6/ does not fit in with the modified specimens. It was decided to determine stress intensity factors for the modified disc specimens by means of photoelastic experiments.

PHOTOELASTIC TESTS

Discs with a diameter of 14o mm were made of epoxy resin and were notched in a similar way as the rocks. The dimensions of the loading prisms and other details were kept at a ratio of 2:1 concerning the real testing equipment and specimens. To study the effect of crack

TABLE 1 - Comparison of K_{Ic} values determined by TPB and disc specimens.

Kind of rock	Type of specimen		Stress Intensity Factors /N/mm-3/2/ Conventional formulas	Modified formula
Andesite tuff	TPB	A	22.3	-
		B	22.0	-
		C	22.4	-
		D	19.8	-
	Disc	E25	118.1	42.7
		E20	187.2	38.1
		E15	125.8	39.5
		E10	100.0	39.3
		F20	79.6	39.3
		F15	103.6	39.1
		F10	127.7	39.8
		G15	66.7	42.0
		G10	77.9	43.1
Compact lime-stone	TPB	A	32.3	-
		B	30.8	-
		C	37.8	-
		D	47.7	-
	Disc	E25	91.6	34.9
		E20	89.0	35.5
		E15	105.9	42.4
		E10	138.1	38.6
		F20	74.2	37.1
		F15	75.7	47.6
		F10	76.9	44.9
		G15	62.2	48.9
		G10	62.4	52.9

length, three different notch depths were used, a = 3o, 44 and 58 mm, while W = 114 mm according to the nomination of Fig.4.

The discs were loaded in a rig and the fringe patterns created by transmitted polarized light were fixed by photographs. The mutual position of polarizers was altered to get a combined fringe pattern containing the integer, the half and the quarter fringe orders too. A drawing of the combined fringe patterns constructed from a series of photographs is given in Fig.5. A concentration of the fringes can be observed around the crack tip and in the vicinity of the loading prisms. It is prominent that the fringe patterns under the prisms are not symmetrical with respect to the prisms and this indicates that the direction of the load is not perpendicular to the surface as it was expected. The resulting load is inclined according to the friction force between the prism and the test piece. Therefore the influence of the friction has to be taken into consideration. To study the effect of friction, the roughness of the contact surface of the specimens and prisms have been varied in the course of experiments.

On the basis of patterns like the one in Fig. 5 the stress intensity factor can be determined. The procedure is described in detail by Ruiz /7/ and also by Thamm /8/. It can be shown that

$$(\sigma_1 - \sigma_2) = K_I \frac{1}{\sqrt{2\pi y_k}} \quad \text{Nmm}^{-2} \qquad \ldots\ldots\ldots /1/$$

where σ_1 and σ_2 are the principal stresses and the values of $/\sigma_1 - \sigma_2/$ are represented by the fringe loops. y_k is the distance from the crack tip, perpendicular to the crack plane.

To eliminate the effect of the occasional load as well as the thickness of the specimen both sides of Equ./1/ are multiplied by B/F, where B is thickness and F is load. Plotting

$$(\sigma_1 - \sigma_2)\frac{B}{F} = \langle \sigma_K \rangle \quad \text{mm}^{-1} \qquad \ldots\ldots\ldots /2/$$

as a function of

$$\frac{1}{\sqrt{2\pi y_k}} \quad \text{mm}^{-1/2} \qquad \ldots\ldots\ldots /3/$$

the points lie on a straight line as seen in Fig.6, the tangent modulus of which is

$$\mathcal{K} = K_I \frac{B}{F} \quad \text{mm}^{-1/2} \qquad \ldots\ldots\ldots /4/$$

The variation of $\mathcal{K}$ as a function of the friction coefficient $/\mu/$ and of the notch depth /a/W/ is shown in Fig. 7 and 8 resp.

Since according to the general form

$$K_I = \sigma \sqrt{a}\, Y \quad \text{Nmm}^{-3/2} \qquad \ldots\ldots\ldots /5/$$

it can be written that

$$K = \sigma \sqrt{a}\, Y \frac{B}{F} \text{ mm} \qquad \text{........ /6/}$$

The nominal stress in the critical cross section consists of two parts: σ_B bending stress and σ_T tensile stress

$$\sigma = \sigma_B + \sigma_T \quad \text{Nmm}^{-2} \qquad \text{........ /7/}$$

where

$$\sigma_B = \frac{6F}{2B}\left[d + \left(a' + \frac{W'-a'}{2}\right) tg\,\psi\right]\frac{1}{(W'-a')^2} \ldots /8/$$

and

$$\sigma_T = \frac{F}{2B}\, tg\,\psi \frac{1}{(W'-a')} \qquad \text{........ /9/}$$

The indication of d, a', W' and ψ can be seen in Fig.9.

It should be pointed out that because the friction shifts also the starting point of distances a and W /see Fig.4/, it seems to be reasonable to use rather a' and W', which are independent of it.

Substituting Equs./8/ and /9/ into Equ./6/ we get

$$K = \frac{\sqrt{a'}}{2(W'-a')}\left[\frac{6}{(W'-a')}(d + a'\, tg\,\psi) + 4\, tg\,\psi\right] Y \ldots /10/$$

From this expression the only unknown quantity, Y may be calculated. For the geometries and conditions examined Equ./10/ yielded Y = 0.65 as a mean value with a scatter less than ±5 per cent.

FINAL RESULTS AND DISCUSSION

The data received by the modified disc specimens have been recalculated using the combined formula of Equs. /4/ and /10/ as well as a value of 0.65 for Y. The distance d in our case was 2.88 mm. The friction between steel and the rocks in question has been measured reproducing the quality of surfaces of the loading prisms and the specimens. The angle φ was 8°45' for andesite tuff and 11°20' for limestone resulting a μ, friction coefficient of 0.1545 for andesite tuff and

0.2016 for limestone. The angle ψ can be calculated as $45^o - \varrho$.

As indicated in Fig.4 nine groups of specimens have been examined varying the diameter and the thickness. All the calculated values were plotted in Fig.10 grouping them according to the dimensions. The comparative values received by the TPB specimens are also given. The mean values of the groups are summarized in Table 1.

It is obvious that the agreement of the results of TPB and disc specimens is much better taking into account also the great scatter, which is a consequence of the structure of the rocks.

The values of andesite tuff confirm the fact that this is a fine-grained rock of porphyric texture, containing weathered feldspars and it can be considered as homogeneous to the scale of testing. The somewhat lower results of TPB tests can be explained by the effect of non-uniform load distribution and high stress concentration at the loading rolls as mentioned earlier.

The results of compact limestone show a definite influence of dimensions. The bigger the test piece, the lower the values of K_{Ic} calculated. This is also the consequence of the structure, since limestone is heterogeneous i.e. it contains 0.5-1 mm thick long cracks filled with calcite crystals. Because of these cracks the probability of fracture increases with the volume tested.

An important conclusion of the research work is that even a small change in the specimen form or in the testing arrangement may decisively alter the loading configuration and therefore a detailed stress analysis is needed before the usual formulas or factors are applied.

SYMBOLS USED

a = crack /notch/ length /mm/

B = specimen thickness /mm/

d = displacement of loading prism from centre line /mm/

D = diameter of disc specimens /mm/

F = loading force /N/

K = stress intensity factor /$Nmm^{-3/2}$/

χ = specific stress intensity factor /$mm^{-1/2}$/

L = length of TPB specimens /mm/

μ = friction coefficient

ψ = angle of resultant load /deg./

φ = angle of friction force /deg./

σ = stress /Nmm^{-2}/

y_k = distances of fringe-loops from crack plane /mm/

Y = geometrical factor

W = width of specimens /mm/

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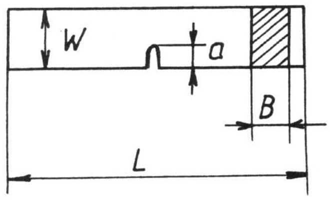


Type	W	B	a	L
A	40	40	20	160
B	40	20	20	160
C	20	40	10	70
D	20	20	10	70

Figure 1 TPB specimens.

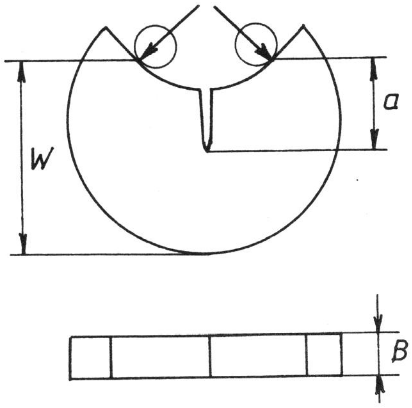


Figure 2 Disc specimens according to Ref. /6/.

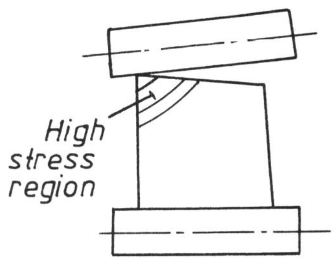
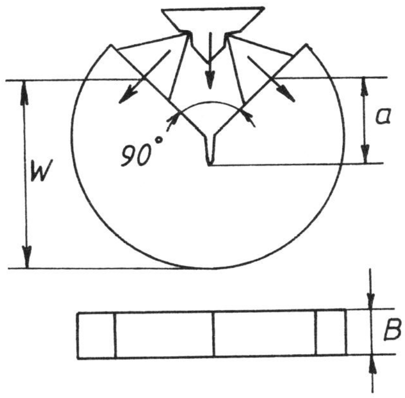


Figure 3 Stress concentration due to inaccuracy.



Type	E25	E20	E15	E10
D		75		
B	25	20	15	10

Type	F20	F15	F10	G15	G10
D		56		32	
B	20	15	10	15	10

Figure 4 Shape and dimensions of modified discs.

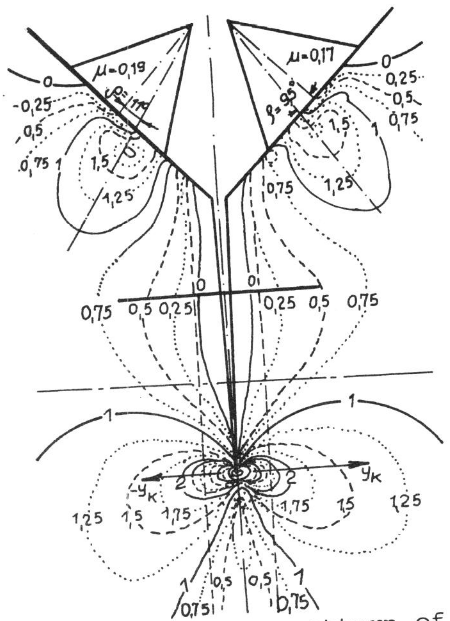


Figure 5 Fringe pattern of a photoelastic model.

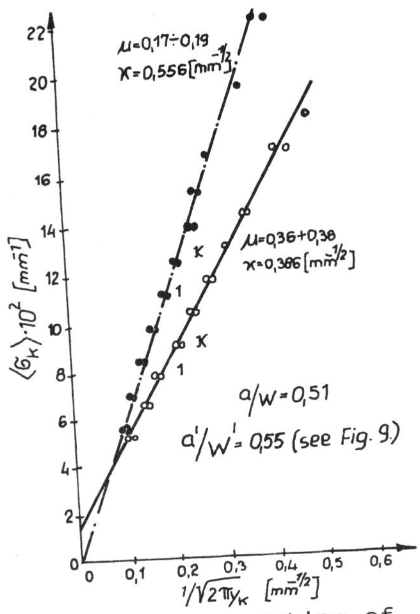


Figure 6 Construction of lines yielding $\mathcal{K}$.

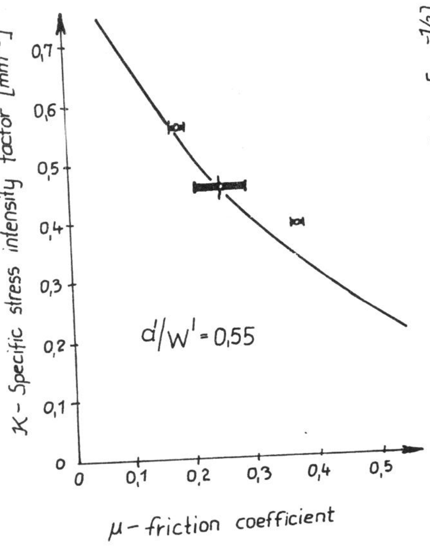


Figure 7 Measured $\mathcal{K}$ values as a function of friction.

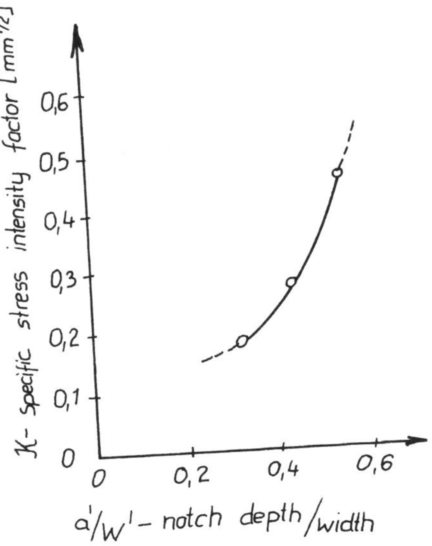


Figure 8 Measured $\mathcal{K}$ values as a function of /a'/W'/ratio.

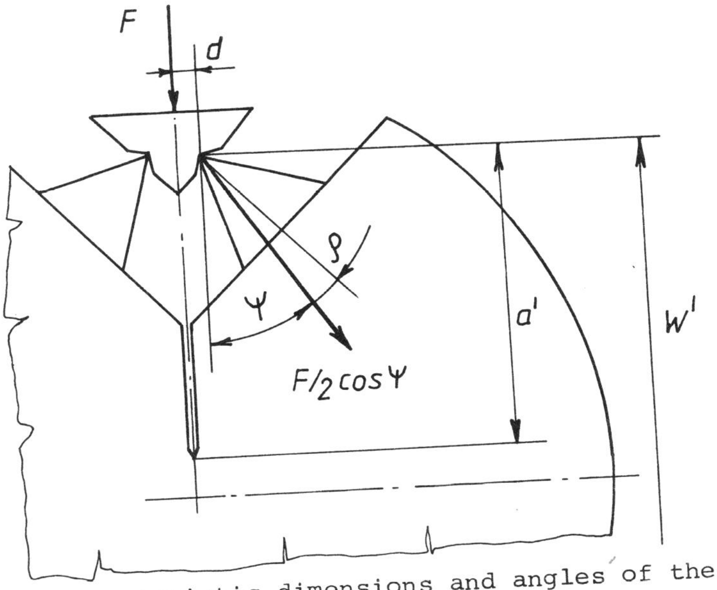


Figure 9 Characteristic dimensions and angles of the modified disc specimen.

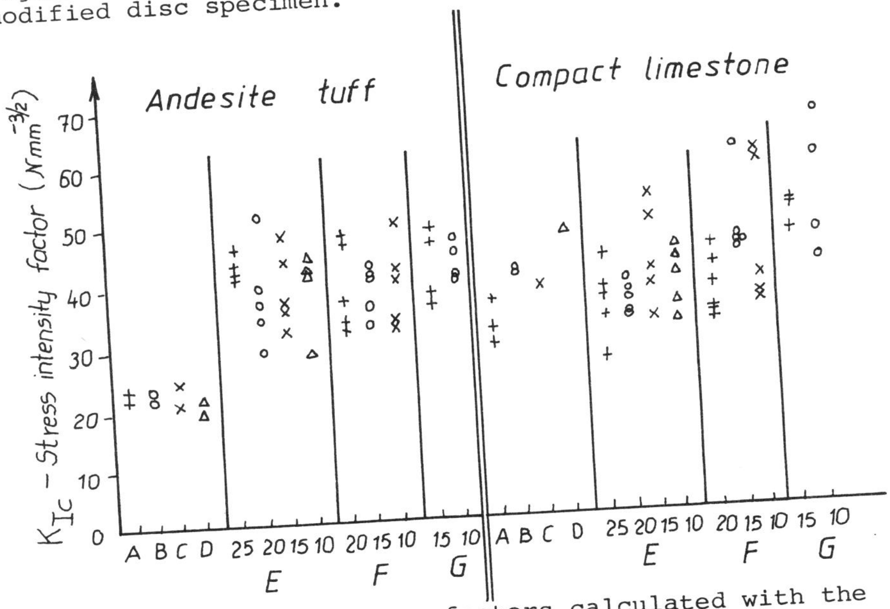


Figure 10 Stress intensity factors calculated with the modified formula and compared to those of TPB tests.