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암석의 파괴역학적 특성과 미세구조에 관한 연구

백환조*

Fracture Properties and Microstructural Characteristics of Rock

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ABSTRACT

금속과 같은 균질한 재료의 균열파괴의 특성을 설명하기 위하여 도입된 파괴역학의 이론들은 1960년대 이후 콘크리트나 암석 등에 대하여 적용되기 시작하였다. 파괴인성계수(fracture toughness)는 균열의 성장에 대한 재료의 저항을 나타낸다. 그러나, 암석의 파괴역학적 특성은 암석이 갖는 불균질성이나 비등방성에 의하여 영향을 받는다. 즉, 암석의 파괴역학적 특성의 측정은 시험편의 크기나 초기균열의 길이, 시험편의 형상 등에 의하여 측정자료의 분산이 심하며 따라서 다른 기본 물성들의 경우에서와 마찬가지로 일정한 시험기준의 도입이 요구되었다. 1988년에 국제암반공학회(ISRM)에서 제시한 표준시험방법은 시험편의 제작이나 시험방법에 있어서 복잡한 과정을 요구하고 있다. 본 논문에서는 표준시험방법에서 사용되는 시험편의 형태에 비하여 비교적 간단한 시험방법들에 의하여 얻어진 파괴인성계수들을 서로 비교하여 제시하고 시험편의 크기와 기타 시험조건에 따른 파괴인성계수 측정치의 변화를 나타내고 있다. 또한, 암석에 포함되어있는 자연균열들의 특성과 파괴역학실험 중 유발되는 인공균열들의 형태를 비교하여 실험실에서 얻은 파괴역학적 계수들의 현장적용에 대한 문제점들을 지적하고 있다.

1. Introduction

For a routine application of fracture mechanics principles to rock engineering problems, the fracture processes and fracture mechanics parameters of rock materials should be better understood for various rock types encountered in the field. Variability in the measured fracture

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toughness, most likely due to various weakness planes and pore spaces and anisotropic behavior of the rock, should be thoroughly investigated. The fracture toughness and other fracture mechanics parameters of heterogeneous rock may be affected the specimen size and loading geometry. These parameters will also depend on its mineralogical composition and microstructure of the rock. Grain and pore size distribution, boundary contact characteristics of individual mineral grains and cementing materials are generally believed to influence the measured fracture toughness. The primary objectives of this study are to determine the fracture toughness values of some rock materials and to study the effects of test variables.

In addition to ambient stress and temperature conditions, in situ rock fracture properties are affected by the macro-and microstructures of the rock, and by the distribution and characteristics of natural fractures. The characteristics of natural fractures within the rock mass may be substantially different from those of induced fractures, such as those induced by hydraulic fracturing or experimental fractures in the laboratory.

This may raise concerns about the application of laboratory-measured fracture parameters to the interpretation of geologic features involving natural fractures which have developed over the geologic time. This study therefore includes an investigation of phenomenological differences between fractures of different origins, aiming to a better understanding of natural fractures within the rock.

2. Rock Fracture Toughness Measurement

2.1 Specimen Description

In this study, the mode I fracture toughness values of the Elberton granite, Ellenberger dolostone, Comanche Peak limestone were measured. The Elberton granite is a fine-grained light-grey stone from the Coggins Granite Co., Elberton, GA. The rock is macroscopically homogeneous and commonly used for monuments. The Ellenberger dolostone was from the middle (Gorman Formation) members of the Ellenberger Group, and was obtained from the Vermont Marble Co., San Saba, TX. The rock is light grey to white, and highly brittle with concoidal fracture. The Comanche Peak limestone, from the Featherlite quarry at Cedar Park, TX, is dominantly light-cream colored with bands of darker cream. The rock is very porous and friable, and was composed of uniform rounded fine grains about 1 mm in diameter. Index properties of these rocks are listed in Table 1.

2.2 Specimen Geometries

The ISRM-suggested chevron bend (CB) specimen was primarily used as the reference. Other specimen geometries included the single-edge-cracked round-bar-in-bending(SECRBB), semi-circular bend (SCB), and the notched Brazilian disc specimens. Test geometries and corresponding formula for calculating the fracture toughness are shown in Fig. 1. The specimen diameters employed in

Table 1. Index properties of the tested rock materials (mean ± standard deviation).

Index Property	Elberton Granite	Ellenberger Dolostone	Comanche Peak Limestone
• Dry density [gram/cm^3]	2.62 ± 0.01	2.67 ± 0.01	1.99 ± 0.03
• Poissn's ratio	0.18 ± 0.03	0.30 ± 0.01	0.23 ± 0.02
• Tensile strength [MPa]	12.72 ± 3.74	13.66 ± 2.63	4.38 ± 0.54
• Static Young's modulus [GPa]	52.71 ± 2.68	74.19 ± 0.49	16.03 ± 1.12
• Dynamic Young's modulus [GPa]	30.13 ± 5.91	76.77 ± 2.37	19.42 ± 0.31
• Bending Modulus [GPa]	30.44 ± 4.26	68.96 ± 6.83	19.58 ± 2.54

this study included 25.4 mm, 51.2 mm, and 76.2 mm for three-point bend specimens (CB and SECRBB). For SCB specimens, effects of the specimen thickness and water saturation on fracture toughness were also evaluated. Specimen thicknesses ranged from 6.4 mm to 101.7 mm, with the fixed diameter of 101.7 mm.

2.3 Rock Fracture Toughness

The measured fracture toughness values on the CB and SECRBB specimens are consistent for the different specimen diameters employed in this study, although the material variability of the Ellenberger Dolostone clearly influenced the test results. As listed in Table 2, it was observed that the fracture toughness values measured on the SECRBB specimens were much lower than those measured by the CB specimens. For the CB specimens, the fracture toughness is calculated assuming that the material is perfectly brittle with a flat R-curve behavior (ISRM,1988).

If a material is ideally brittle and free from the subcritical crack growth, then the fracture toughness will be uniquely determined regardless of the assumption employed. However, many rock materials exhibit subcritical crack growth and a slightly rising R-curve behavior (Baek, 1994).

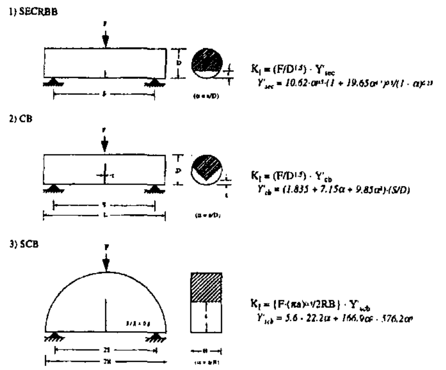


Fig. 1. Test Geometries for Determining Rock Fracture Toughness.

The effects of the specimen thickness and water saturation for the SCB specimens (2R = 102mm) are shown in Table 3. Average values of the fracture toughness of the dry SCB specimens show general trend of decreasing fracture toughness with the increasing specimen

Table 2 Fracture Toughness of the CB and SECRBB specimens (mean±standard deviation).

Rock Types	Diameter (mm)	Fracture Toughness [MN/m$^{1.5}$]	
		Chevron Bend	SECRBB
Elberton Granite	25.4	1.63 ± 0.04	1.35 ± 0.05
	50.8	1.73 ± 0.05	1.37 ± 0.06
	76.2	1.75 ± 0.01	1.48 ± 0.04
Ellenberger Dolostone	25.4	1.42 ± 0.09	1.08 ± 0.14
	50.8	1.62 ± 0.16	1.07 ± 0.04
	76.2	1.63 ± 0.13	1.23 ± 0.10
Comanche Peak Limestone	25.4	0.46 ± 0.03	0.40 ± 0.03
	50.8	0.59 ± 0.03	0.51 ± 0.02
	76.2	0.55 ± 0.02	0.47 ± 0.06

thickness. This trend, however, is not apparent for the water-saturated specimens. the effect of water saturation is evident for the Elberton granite and Comanche Peak limestone, with fracture toughness reductions ranging 10 to 20 percent for the granite, and up to 33 percent for the limestone specimens.

However, the low-porosity brittle Ellenberger dolostone showed no significant effect of water saturation. The effect of moisture content on the fracture toughness field condition and core integrity must be maintained for valid determination of the fracture toughness of rock materials.

3. Crack Surface Morphology

Even under controlled test conditions in the laboratory, the scatter in the measured fracture toughness is often significant for some rock materials. This is largely due to the material characteristics of intact rocks, including variations in grain mineralogy. The scatter will also include the superimposed effect of geologic history which has resulted in diagenetic stress state and temperature changes which impact rock fabric, porosity, and physical properties.

The question under study is, therefore, whether fracture properties can provide insight as to when and how the natural fracture were developed.

3.1 Sample Description

The Sonora Canyon sandstone is one of the "Canyon Sands (late Pennsylvanian or early Permian) intervals that exist in the Val Verde Basin of southwest Texas. The lithology is mostly fine-grained sublitharenites and litharenites, and authigenic cements and replacive minerals are frequently observed. Major diagenetic events were siderite ($FeCO_s$) / chlorite cementation, mechanical compaction, quartz cementation, feldspar dissolution and illite and kaolinite precipitation, and

Table 3. Fracture Toughness of Dry and Wet SCB Specimens (mean ± standard deviation).

Rock Types	Thickness (mm)	Fracture Toughness [$MN/m^{1.5}$]	
		Dry Specimen	Wet Specimen
Elberton Granite	6.4	1.21 ± 0.01	0.97 ± 0.05
	12.7	1.15 ± 0.03	0.97 ± 0.05
	25.4	1.18 ± 0.03	0.97 ± 0.05
	50.8	1.15 ± 0.03	0.97 ± 0.03
	101.6	1.09 ± 0.05	0.98 ± 0.04
Ellenberger Dolostone	6.4	1.03 ± 0.08	0.87 ± 0.18
	12.7	0.91 ± 0.10	0.98 ± 0.09
	25.4	0.91 ± 0.06	0.94 ± 0.05
	50.8	0.89 ± 0.05	0.92 ± 0.05
	101.6	0.86 ± 0.05	0.91 ± 0.06
Comanche Peak Limestone	6.4	0.52 ± 0.04	0.35 ± 0.02
	12.7	0.48 ± 0.01	0.32 ± 0.03
	25.4	0.47 ± 0.03	0.34 ± 0.02
	50.8	0.45 ± 0.02	0.34 ± 0.03
	101.6	0.35 ± 0.02	0.33 ± 0.01

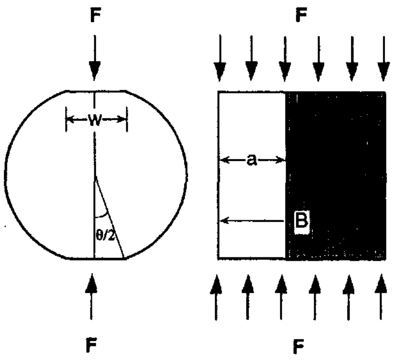
finally, ankerite cementation (Hamlin *et al.*, 1992).

Preliminary studies on the Sonora Canyon sandstone core showed sandstone variability and apparent lithologic control of the distribution of natural fractures in recovered cores. Siderite-cemented layers have higher porosity and also higher population of natural fractures, compared to non-siderite (secondary quartz or clay minerals) -cemented layers. Natural fractures are short (less than 100 mm long) and vertically discontinuous, with apertures generally less than 0.35 mm (Marin *et al.*, 1993). The main fracture-filling minerals are calcite, quartz, and dickite.

3.2 Fracture Properties Testing

The Sonora Canyon sandstone cores, 101.6 mm in diameter, studied here were obtained from the extensive core collection at the Core Research Center of the Bureau of Economic Geology, The University of Texas at Austin. Fracture toughness for each sandstone type, siderite- or non-siderite-cemented sandstones was measured for the same crack orientation as that of natural fractures. The notched Brazilian disc specimen were mainly used for fracture toughness measurements, because the CB and SECRBB specimen geometries were not applicable due to limited amount of intact rock materials. Furthermore, the crack orientation induced by those specimen geometries would be parallel to bedding, an unrepresentative direction for comparing natural and experimental fracture morphologies, considering the fact that natural fractures observed in the core specimens are mostly orthogonal to bedding.

Notched Brazilian disc specimens, 50.8 mm in diameter and 40 to 50 mm thick, were prepared from both siderite- and non-siderite-cemented core intervals. A total of 30 (13 siderite- and 17 non-siderite-cemented sandstones) specimens were tested. The test geometry is shown in Fig. 2.



$$K_{Ic} = 1.264\,(\sin 2\theta - \theta)\,\frac{F_{max} \cdot a^{0.5}}{w \cdot B}$$

Fig. 2. Notched Brazilian Disc Specimen.

Fracture toughness values of both siderite- and non-siderite-cemented sandstones are summarized in Fig. 3. As indicated in Fig. 3, the difference in average fracture toughness values of the two lithologic materials is negligible. The similarity in the measured fracture toughness indicates that the fracture toughness of current rock materials does not explain the difference in fracture occurrence between the two materials. It is possible that the apparent higher population of natural fractures in thin siderite-cemented layers is due to the commonly observed relationship between the fracture spacing and bed thickness.

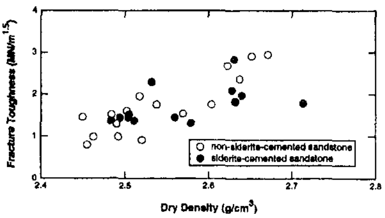


Fig. 3. Fracture Toughness vs. Dry Density of the Canyon Sandstone.

3.3 Micropetrographic Techniques

In order to compare results of fracture processes under contrasting conditions, surface morphology of 5 natural (N) and 5 experimental (E) fractures was evaluated using a petrographic microscope, and both qualitative and quantitative roughness criteria were applied. Natural fractures were sampled from the Canyon sandstone cores, and experimental fractures were obtained from the specimens tested for fracture toughness measurements. Thin-sections, containing either natural fractures or experimental fractures, were cut parallel to the direction of crack propagation. To document morphological differences between different fracture types, thin sections were moved in increments of 300㎛ along a reference line. Attributes along the reference line were counted to describe crack surface morphology.

At each point, the following information was obtained: (a) upward or downward deviation of crack propagation path from reference line, and (b) crack propagation types. The crack propagation type was characterized as either transgranular crack increment (that is, crack pathway crossing individual grains), or intergranular crack increment (that is, crack pathway crossing cement or pore space, or following grain boundaries).

3.4 Crack Propagation Types

Figure 4 shows percent cumulative lengths of both intergranular and transgranular crack propagation observed in natural and experimental fracture. Percent length is defined as the ratio of length occupied by a certain crack type, either intergranular or transgranular, to total crack length. Dotted lines represent cumulative increments of intergranular propagation, and solid lines represent transgranular propagation. For cracks in this study, deviation from a straight reference line is commonly related to intergranular crack propagation. The crack front takes less resistant paths by extending through weaker off-line grains or cement.

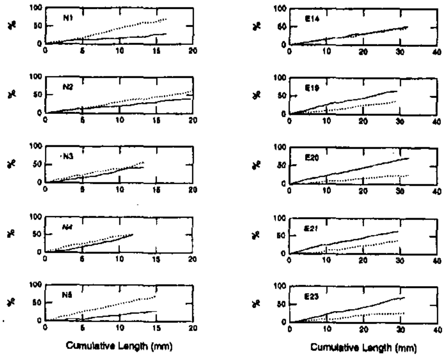


Fig. 4. Propagation Characteristics of Natural and Experimental Fractures.

As indicated in Fig. 4, intergranular propagation prevails in natural fracture, whereas transgranular propagation is dominant in experimental fracture. Unlike natural fractures, propagation behavior of experimental fractures does not appear to vary with different cement type. Figure 4 also shows initially flat curves of percent intergranular propagation for initial crack extension from the notch tip was mostly transgranular, whereas percent intergranular propagation increased as crack propagation continued.

Therefore, it is evident that the fracture toughness values measured from the peak load and initial crack extension do not necessarily represent the whole process of the crack propagation.

3.5 Roughness of Crack Surface

Roughness of a fractured surface, depicted in Fig. 5, can be described by several statistical terms including the maximum asperity height $h_{\max}$, mean asperity height h_{ave}, standard deviation of heights SD_h, mean asperity angle i_{ave}, and standard deviation of angles SD_i. Maximum asperity height is the height difference between highest and lowest points on a profile. Other terms are calculated by (Lam and Johnston, 1985):

$$h_{ave} = \frac{1}{L} \cdot \int_0^L |y| \, dx$$

$$i_{ave} = \tan^{-1}\left[\frac{1}{L} \cdot \int_0^L \left(\frac{dy}{dx}\right) dx \right]$$

$$SD_h = \sqrt{\frac{1}{L} \int_0^L (|y| - h_{ave})^2 \, dx}$$

$$SD_i = \tan^{-1} \cdot \sqrt{\frac{1}{L} \int_0^L \left(\frac{dy}{dx} - \tan i_{ave} \right)^2 dx}$$

Statistical parameters describing surface roughness of both natural and experimental fractures are listed in Table 4. As shown in this table, the parameter SD_i shows a clear distinction between natural and experimental fractures. This reflects rougher surface profiles of natural fractures, since a low SD_i value indicates smoother surfaces. However, other statistical parameters do not clearly distinguish between the two fracture types.

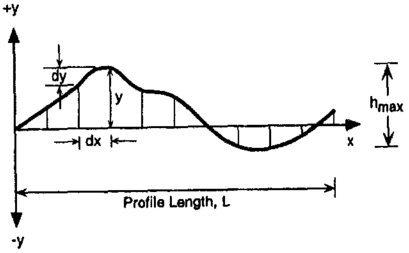


Fig. 5. Roughness Profiles of the Fracture Surface (*from* Lam and Johnstone, 1985).

Among natural fractures sampled from siderite-cemented sandstones, specimens N2 and N3 have thicker siderite cement rims compared to those of N1 and N5. Higher values SD_i may show that thicker siderite rims are weaker and make the rock more prone to grain-boundary fracture under natural loads. Results for experimental fractures also exhibit a similar trend. For each grouping of natural and experimental fractures, siderite-cemented sandstones have higher values of all parameters, which indicates rougher profiles. This conclusion agrees well with measurements of percent intergranular crack propagation.

4. Conclusions

From the results of this study, the following subjects are recommended for future studies:

1. Instead of relatively sophisticated sample preparation and test procedures of

Table 4 Statistical summary of the inter- and transgranular propagation of natural (N) and experimental (E) fractures.

Specimen	Cement	h_{max} [mm]	h_{ave} [mm]	SD_h [mm]	SD_i [degrees]
N1	siderite	0.83	0.28	0.16	12.1
N2	siderite	0.82	0.24	0.17	17.8
N3	siderite	1.10	0.24	0.15	17.6
N4	non-siderite	0.70	0.18	0.12	10.3
N5	siderite	0.63	0.20	0.16	12.1
E14	siderite	1.16	0.23	0.16	2.2
E19	siderite	1.09	0.17	0.19	3.4
E20	siderite	1.09	0.30	0.23	4.7
E21	non-siderite	0.83	0.15	0.13	2.7
E23	non-siderite	0.85	0.17	0.14	2.6

the ISRM-suggested test methods, more simplified test methods need to be standardized for rock fracture toughness measurements. The SCB and notched Brazilian disc specimen types are quite attractive and, therefore, further study on the test procedures and calibration techniques for these specimen types is required.

2. Characteristics of fractures with different origins, in propagation behavior and surface morphology, should be investigated further to permit more reliable interpretation and applications of laboratory-measured fracture mechanics parameters. The morphological differences and similarities between hydraulic and experimental fractures, for example, would lead to better understanding of uncertainties involved in the performance of the hydraulic fracturing.

References

[1] Baek, H., Evaluation of Fracture Mechanics Properties and Micro-structural Observations of Rock Fractures: Ph. D. Dissertation, Department of Civil Engineering, The University of Texas at Austin, Austin, TX, 200 p., 1994.

[2] Hamlin, H. S., Clift, S. J., and Dutton, S. P., Stratigraphy and Diagenesis of Sonora Canyon Deep-Water Sandstones, Val Verde Basin, Southwest Texas: *Transactions*, American Association of Petroleum Geologists, Southwest Section, pp. 209-220, 1992.

[3] ISRM Commission on Testing Methods, Suggested Methods for Determining the Fracture Toughness of Rock: *Int. J. of Rock Mech. and Min.Sci. & Geomech. Abstr.*, Vol. 25, No. 2, pp 71-96, 1988

[4] Lam, T. S. K. and Johnston, I. W., A Scanning Device to Quantify Joint Surface Roughness: *Geotechnical Testing Journal, GTJODJ*, Vol. 8, No. 3, pp 117-124, 1985.