Experimental Investigations on the Relationships Between Rock Toughness And Physical Properties of Shale

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***Abstract* — The relationship between shale toughness and its mechanical parameters is of significant importance to predict the shale toughness at great depth based on geophysical logging data. In this paper, a large number of experiments are performed for toughness measurement of artificial shale specimens of thick-wall cylinder, with internal pressures applied. And the finite element method is used to interpret the toughness. The acoustic speeds of the specimens are gauged with the acoustic instruments made by Hewlett Packard, and the relationship between the shale toughness and its mechanical parameters were determined.**

Keywords - rock toughness, physical properties, finite element method

I. Introduction

In many reservoirs of oil and gas, usually shale acts as the effective barrier layer, while sandstone is the pay-zone. The criterion for fracture propagation is very important during hydraulic fracturing treatment[1]. The hydraulic fracturing treatment will fail if the hydraulically induced fracture breaches the thin barrier layers and meets water layer or formation with low pressure[2]. In order to ensure the propagation of hydraulically induced fracture within the designed scope, the relationship between stress intensifying factor and the toughness of barrier formations must be taken into consideration to perform the effectual treatment designs.

Vast attempts are being made to predict the fracture toughness of rock materials on the basis of the relationship between the fracture toughness of rock and other mechanical parameters, especially in present rock mechanics[3]. In petroleum engineering, the geo-physical logging data can reflect the formation properties of measured formations, including acoustic logging, density logging, and natural gamma logging, obtained by continuous measurement along the uncased well-bore of target formations[4]. Thus continuous formation properties such as elastic parameters and other physical mechanical parameters could be calculated. Whittaker[5]etc. gave an elaborate and extensive summary of literatures on this aspect, and revealed that good relevance exits among fracture toughness, hardness index, uni-axial tensile strength, uni-axial compressive strength, and elastic modulus. Zhixi Chen[6]performed tentative research on the relevant relations between acoustic speed and fracture toughness of rock materials.

It is necessary to study and propose the method to predict the fracture toughness of rock materials at great depth, for sophistication of direct measurement of fracture toughness and heavy cost of getting core samples out by drilling operation[7]. At present, the related research on this abroad and home is few, according to close and careful literature search and study. In this paper, fracture toughness of rock samples is measured as well as the physical mechanical parameters, meanwhile the statistic relationship between fracture toughness and these physical mechanical parameters is established. For steadiness of deriving these parameters directly or indirectly from the data of geo-physical logging, it is very convenient to be applied to predict the fracture toughness of rock material underground.

II. Measurement for Rock Fracture Toughness

The first step is to cut the core into segments of about 45 mm in height, while making the two corresponding circular surfaces parallel and smooth. The outer diameter of the specimens is about 100mm, with the inner diameter of the hole along the central line about 10mm. And then two symmetrical fractures with width of 3~4 mm about the central line are manufactured along the radial direction. After all these steps, a section of rubber tube with inner diameter of 6mm and outer diameter of 9mm is put into the inner hole of the specimen. Fluid pressure is applied only on the surface of the inner hole, not on the fracture surface, when pressured fluid is pumped into the rubber tube. A certain of Lubrication oil is put on the two surfaces in order to offset the influence of boundary effect on fracturing process. Then rock specimen is mounted onto the experimental device inside the axial compressive equipment. Before pressured fluid is pumped, some small axial force is applied, in the light of sealing. If confining pressure is needed in the experiment, the confining pressure is applied in advance. Then quasi-static fluid pressure (1MPa per minute) is applied into the rubber tube by the MTS286 Servo-hydraulic Pressure Intensifier, until the specimen breaks. The specimen is thought to fail when the pressure displayed on the data acquisition system starts to fall. And the pressure and fluid volume pumped are being recorded automatically by the data

TABLE I. SPECIMEN DIMENSIONS AND EXPERIMENT RESULTS OF K_{IC}

No.	Clay Content	Fracture Length L (mm)	Outer Diameter 2b (mm)	Inner Diameter 2a (mm)	b/a	L/(b-a)	Confining Pressure (MPa)	Fracturing Pressure (MPa)	K_{IC} $MPa\bullet\sqrt{m}$
1-1	0.6	4.4	96.75	10	9.6750	0.1014	0	1.38	0.1102
1-2		3.86	95.74	10.3	9.2951	0.0904	2.5	8.294	0.9307
1-3		4.135	96.7	10.25	9.4341	0.0957	5	10.153	1.5098
1-4		4.685	97.82	10.35	9.4512	0.1071	7.5	13.152	2.2348
1-5		4.57	96.92	10.25	9.4556	0.1055	10.2	17.47	2.9843
1-6		4.675	97.63	10.3	9.4786	0.1071	13.2	16.15	3.5084
1-7		4.92	96.68	10.35	9.3411	0.1140	14	16.085	3.7406
1-8		4.285	97.03	10.3	9.4204	0.0988	15.2	18.789	3.9381
1-9		4.385	97.89	10.3	9.5039	0.1001	17.1	26.045	4.7413
1-10		5.015	95.6	10.35	9.2367	0.1177	20	21.42	5.2975
2-1	0.3	4.305	97.1	10.4	9.3365	0.0993	0	3.27	0.1935
2-2		4.565	97.3	10.45	9.3110	0.1051	2.6	18.369	1.6004
2-3		4.695	97.46	10.3	9.4621	0.1077	4.9	28.278	2.6279
2-4		4.215	97.32	10.35	9.4029	0.0969	7	32.85	3.2279
2-5		4.975	96.84	10.5	9.2229	0.1152	10	29.104	3.7735
2-6		4.52	96.63	10.6	9.1160	0.1051	12.4	28.887	4.1417
2-7		4.62	95.69	10.35	9.2454	0.1083	15.5	25.839	4.5481

acquisition system connected with computer, during experiment. Also acoustic emission is monitored with LOCAN—AT14 for accurate specification of fracture initiation and propagation against the pressure abrupt fall. A pair of probes for acoustic emission during fracturing is attached onto the cylindrical surface of the piston. The vacuum oil is needed to act as the coupling agent between the probes and the piston surface to reduce the energy loss during acoustic propagation. Refer to the figure 1 for the experimental diagram.

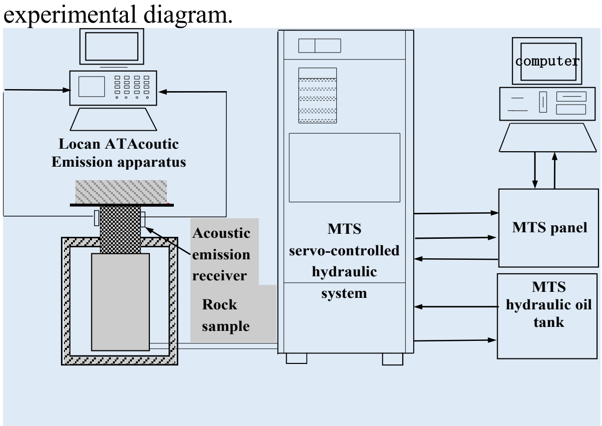


Figure 1. Flow chart of experiments for toughness.

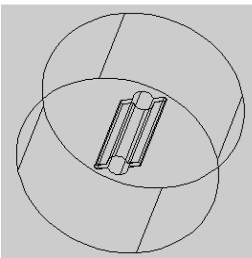


Figure 2. Three-dimensional schematic representation of specimens.

III. INTERPRETATION OF ROCK TOUGHNESS

Suppose a two-dimensional strain problem, zero fracture-tip radius only in fracture formula, elastic material behavior with small deformation [8].

$$K_I = \frac{1+\left(R_i/R_0\right)^2}{1-\left(R_i/R_0\right)^2} p\sqrt{\pi a}\times K^* \qquad (1)$$

where as, K_I is SIF, R_i and R_0 are inner diameter and outer diameter of the thick wall cylinder respectively, α is the pre-fracture length, p is the internal pressure on the inner surface of samples, and K^* is a coefficient decided by R_0/R_i and $\alpha/(R_0-R_i)$ from some specified graphs (refer to Fig3. for the example graph). The critical SIF, i.e. fracture toughness, is calculated when the inner pressure corresponds to the failure occurrence.

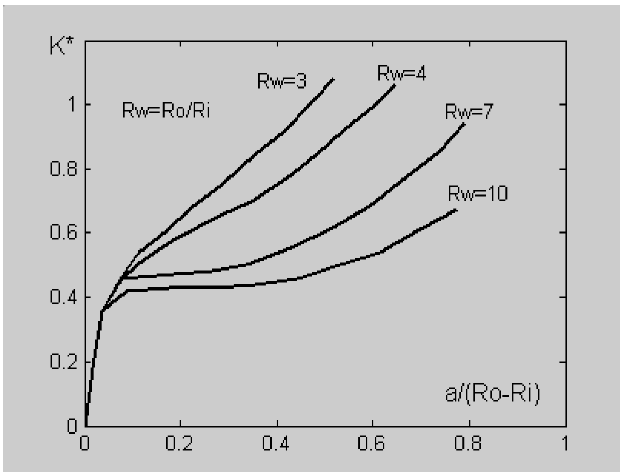


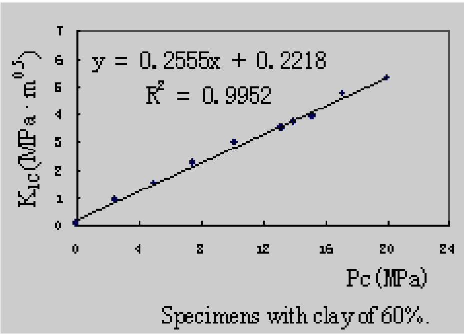
Figure 3. Chart for manual calculation of K_{IC}.

IV. RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND CONFINING PRESSURE

The fracture toughness experiments are carried out for specimens with clay of 60% and 30% respectively, under confining pressure conditions, and under laboratory temperatures, with specimen parameters and experiment results listed in the Table 1.

It should be noted that the fracture toughness is calculated with the help of finite element model established by the author in other papers.

With the help of statistic methods, the relationship between fracture toughness K_{IC} and confining pressure Pc is regressed as in the Figure 4.



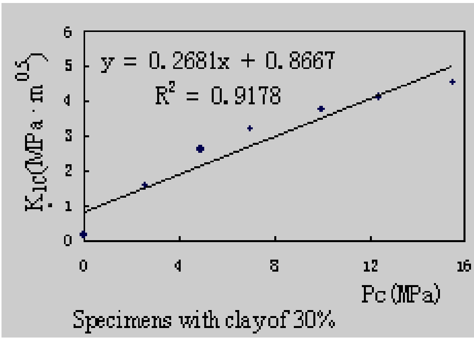


Figure 4. Relationship between toughness and confining pressure.

It is evident that the fracture toughness is proportional to the confining pressures, and toughness under zero confining pressure may be far below those under confining pressure conditions, especially when the confining pressure is high. For this reason, the fracture toughness under confining pressures should be used in the practical engineering, rather than the ones under zero confining condition to avoid great error.

V. RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND PHYSICAL MECHANICAL PARAMETERS

See table 2 for the parameters of specimens: fracture toughness KIC, density ρ , compressive wave velocity Vp , shear wave velocity Vs , uni-axial compressive strength σ_c , and elastic modulus, in which acoustic velocities are measured with acoustic velocity apparatus of HP company of US, and uni-axial compressive strength and the static elastic modulus are measured with MTS system, and dynamic elastic modulus is calculated from measured acoustic velocity. In elastic mediums, the relationship between the dynamic elastic modulus and the compressive & shear wave velocities is as in formula (2) [9][10].

Take rock material as an infinite elastic body with isotropic properties, the dynamic elastic modulus can be obtained from the compressive wave velocity and the shear wave velocity:

$$E_d = \rho V_s^2 (3V_p^2 - 4V_s^2)/(V_p^2 - V_s^2) \tag{2}$$

where, E_d is dynamic elastic modulus，V_p is compressive wave velocity，V_s is shear wave velocity，ρ is density.

The relationships between fracture toughness and acoustic velocity, elastic modulus, clay content and uni-axial compressive strength are shown from Figure 5 to Figure 8.

TABLE II. PHYSICAL MECHANICAL PROPERTIES OF SPECIMENS

No.	V_{cl}	V_s (m/s)	V_p (m/s)	ρ (kg/m³)	E_d (GPa)	E_s (GPa)	σ_c (MPa)	K_{1C} (MPa.m$^{0.5}$)
1	0.0	2294.372	3566.022	1763.200	21.2888	17.1468	63.154	0.2873
2	0.1	2171.458	3281.614	1733.256	18.1524	11.4829	52.175	0.2397
3	0.2	1985.459	2946.058	1699.993	14.5277	9.8324	33.344	0.2007
4	0.3	1866.159	2781.833	1643.890	12.4903	6.8480	31.394	0.1935
5	0.4	1711.522	2501.537	1578.772	9.8039	6.4017	20.393	0.1743
6	0.5	1640.408	2400.000	1486.223	8.4914	3.1165	14.207	0.1497
7	0.6	1534.003	2242.938	1402.013	6.9980	2.8533	9.488	0.1102

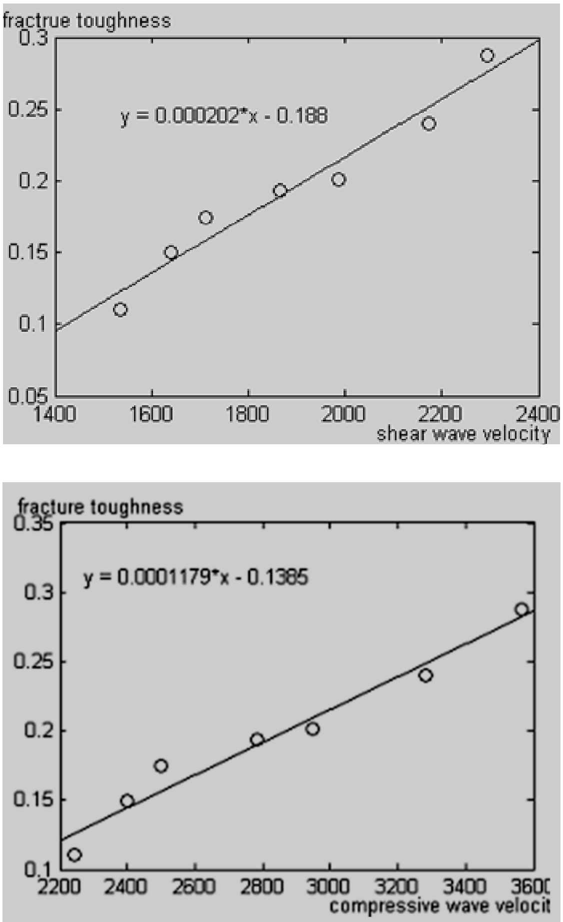


Figure 5. Relationship between toughness and wave velocity.

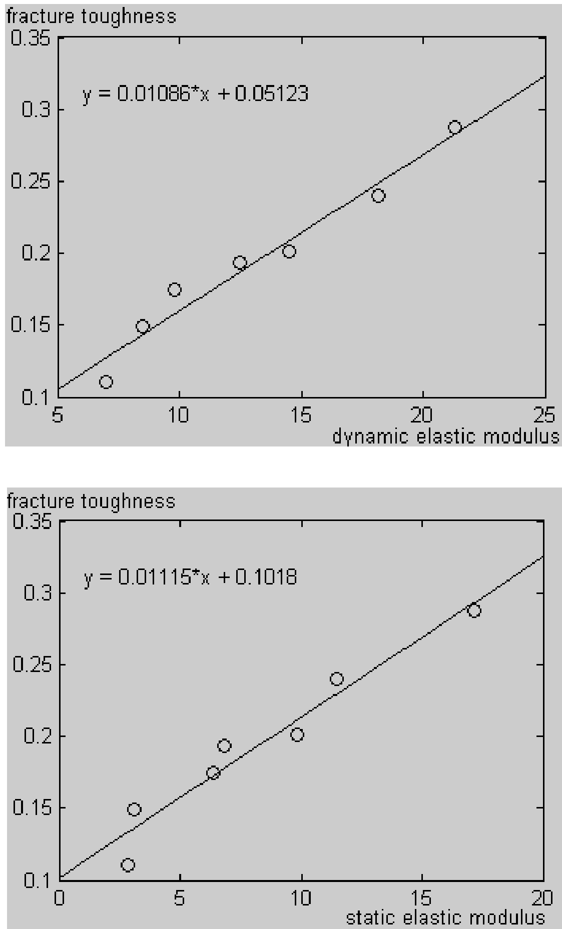


Figure 6. Relationship between toughness and elastic modulus.

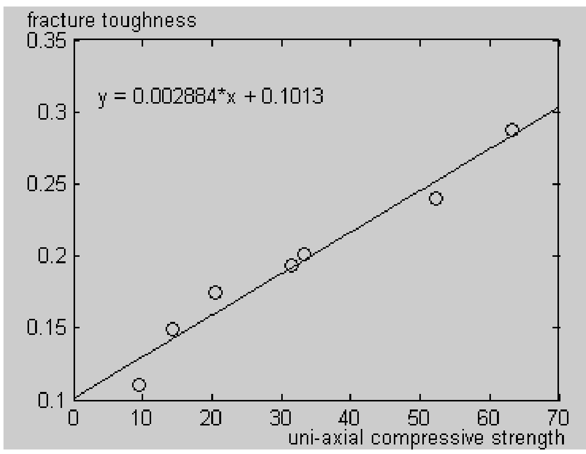


Figure 7. Relationship between toughness and uni-axial compressive strength

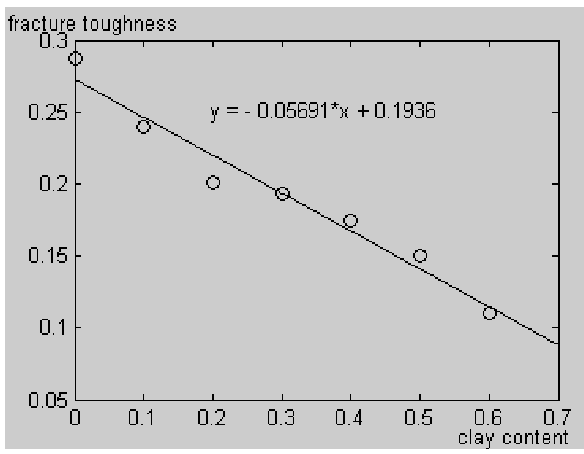


Figure 8. Relationship between toughness and clay content

DOI 10.5013/IJSSST.a.17.49.54

ISSN: 1473-804x online, 1473-8031 print

It is found from statistic results by the least square method that fracture toughness increases linearly with acoustic velocities, dynamic and static elastic modulus, and uni-axial compressive strength, but decreases with clay content.

Formation density ρ, compressive time interval or acoustic velocities V_s , V_p and clay content V_{cl} can be gained from logging data, then rock fracture toughness could be predicted from acoustic logging data, density logging data, and gamma logging data.

VI. CONCLUSIONS

Fracture toughness of shale is measured with thick-wall cylinder specimen under internal pressure, and the relationships between fracture toughness and confining pressure, uni-axial compressive strength, acoustic velocities, dynamic & static elastic modulus, and clay content are presented;

The relationship between fracture toughness and physical mechanical parameters established in this paper provides feasible means to predict fracture toughness from geo-physical logging data at great depth.

ACKNOWLEDGMENT

This work was financially supported by Oil & Gas Technology Research Institute of PetroChina Changqing Oilfield Company.

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