A MODEL OF PERMEABILITY ENHANCEMENT OF COAL UNDER TRIAXIAL COMPRESSION

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ABSTRACT

This work presents a model of permeability enhancement of coal due to prior in-situ fracturing under triaxial compression, as a function of stress history. The first part of the work has involved subjecting coal specimens to pre-set triaxial stress levels and then relaxing the stress levels back to the original confining pressure. Allowing nitrogen to flow through the specimen in a Hoek cell both before and after fracturing, it has been possible to measure the permeability of the specimen in both cases. The second part of the work has involved correlating the permeability change in the coal specimens with the applied deviatoric compressive stress levels. The correlation stress parameter has been chosen in such a novel way as to represent, at any stress condition, how far we are from a fracture strength level. The characterization of fracture strength levels under triaxial compressive stress states has been based on results of previous work by the authors. Consequently, optimization procedures has been employed. In this way, it has been possible to achieve a close agreement between the mathematical model and the experimental data. The present model provides a vital link between in-situ analyses of coal fracturing and in-situ gasification models. Results of combined computer packages containing the various modules can aid engineers in achieving optimum design of an underground coal gasification process. Development of such packages is currently under way at the authors' laboratories. Similar packages can be developed for optimization of enhanced oil recovery processes which require permeability enhancement of anisotropic rock materials such as oil, oil sand, and oil shale formations.

1. INTRODUCTION

In a previous work [1], the compressive fracture strength of coal under triaxial compression has been correlated with the applied stress states for conditions that other factors such as temperature, stress rate, and sample size are held constant.

The failure criterion as proposed in [1] takes the form:

$$\text{For failure,} \quad E \geq f(\bar{\sigma}) \qquad (1)$$

where

$$E = H[(\bar{\sigma}_x - \bar{\sigma}_y)^2 + 6\bar{\tau}_{xy}^2] + G[(\bar{\sigma}_x - \bar{\sigma}_z)^2 + 6\bar{\tau}_{xz}^2] + F[(\bar{\sigma}_y - \bar{\sigma}_z)^2 + 6\bar{\tau}_{yz}^2]$$

$$f(\bar{\sigma}) = \beta_o + \beta_1\bar{\sigma} + \beta_2\bar{\sigma}^2 \qquad for \quad \bar{\sigma} \geq 1$$

$$= 1 \qquad \text{for } \bar{\sigma} < 1$$

$$\bar{\sigma} = \bar{\sigma}_x + \bar{\sigma}_y + \bar{\sigma}_z$$

$\bar{\sigma}_x, \bar{\tau}_{xy}, \ldots$ = nondimensionalized stress components

$$= \frac{\sigma_x}{\sigma_o}, \frac{\tau_{xy}}{\sigma_o}, \ldots$$

σ_o is the lowest uniaxial compressive strength of the material in the respective x,y, or z directions. x, y, z are the principal material directions. H, G, F, β_o,

β_1, and β_2 are experimentally determined constants. Equation (1) can take the form

For brittle fracture (failure),

$$E^{*} \equiv \frac{E}{f(\bar{\sigma})} \geq 1 \qquad (2)$$

The work in reference [1], indicates that the (applied) stress parameter, $E^{*} = E/f(\sigma)$, governs the brittle fracture behavior of coal under multiaxial states of stress.

In the present work, we postulate that permeability variation of various types of coal, corresponding to a controlled low rate fracture process, is related to the fracture behavior of the material under multiaxial states of stress. Consequently, in view of the results presented in reference [1], we postulate that permeability variation of coal under multiaxial states of stress, can be correlated with the (applied) stress parameter, E^{*}.

Based on our postulation, we have carried a series of permeability measurement tests. In each test, a cylindrical coal specimen was subjected to a 1.379 MPa (200 psi) hydrostatic pressure, using a Hoek triaxial cell, to simulate the in-situ overburden stresses. Next, at various levels of gas pressure differential applied at the ends of the specimen, nitrogen was allowed to flow through the specimen and the corresponding flow rates were recorded. The value of the gas pressure differential and the corresponding gas flow rate for the various tests, were then used in conjunction with the basic laws of fluid flow through porous media [2], to determine the Darcy permeability coefficient, k_i.

Next, each sample was subjected to a certain level of axial compression in addition to the 1.379 MPa hydrostatic pressure. Then, when the axial load was removed and the sample was left under the effect of the 1.379 MPa hydrostatic pressure, the new permeability coefficient, k_f, was determined in a manner similar to that used for k_i. Finally, the relative change in the permeability coefficient was estimated by calculating $k^{*} = k_f/k_i$. This process was continued up to a stress state corresponding to the fracture state of the coal according to the fracture strength criterion represented by Eqn. (1). For each stress level, (2-5) specimens were tested and the average of k^{*} was determined. Figures (1) and (2) show the apparatus used for permeability measurements and the details of the Hoek triaxial cell used. The experimental results were used to establish a mathematical correlation between k^{*} and the maximum applied stress state.

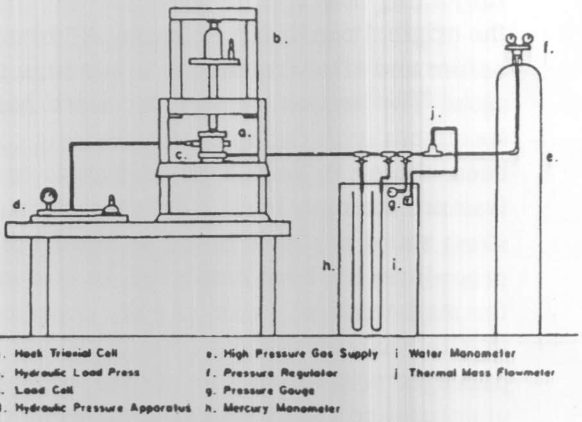

Figure 1. Arrangement of apparatus for permeability measurement.

2. A STRESS-PERMEABILITY MODEL

In the present work, we propose, based on the previous discussion, the following form for the relation between the permeability variation parameter, k^{*}, and the corresponding maximum applied stress state :

$$k^{*} = k_f/k_i = fn(E^{*})$$

$$= C_o + C_1E^{*} + C_2E^{*2} + C_3E^{*3} + C_4e^{\alpha E} \qquad (3)$$

where C_o, C_1, C_2, C_3, C_4, and α, are experimentally determined constants. $E^{*} = E/E$.

For Nova Scotia coal, which was tested in the present work, reference [1] shows that:

$$E = 0.500851\,[\,(\bar{\sigma}_x - \bar{\sigma}_{)}y)^2 + 6\bar{\tau}_{xy}^{\;2} + (\bar{\sigma}_x - \bar{\sigma}_z)^2 + 6\bar{\tau}_{xz}^{\;2} + (\bar{\sigma}_y - \bar{\sigma}_z)^2 + 6\bar{\tau}_{yz}^{\;2}\,]$$

$$\bar{E} = -1.39114 + 2.55387\,\bar{\sigma} - 0.162736\,\bar{\sigma}^2 \quad \text{for } \bar{\sigma} \geq 1$$

$$= 1.0 \quad \text{for } \bar{\sigma} < 1$$

The proposed stress parameter, E^*, is a novel parameter. The value of the stress parameter E^* indicates how far we are from a fracture strength level at any stress state. When $E^* = 1$, the brittle fracture state is reached.

It is to be noted that the present model takes material anisotropy into consideration. Consequently, it is possible to construct similar stress-permeability models for various types of anisotropic rock materials, once the stress parameters governing their brittle fracture behavior are identified. Work such as reference [3], helps identify such parameters.

3. CORRELATION BETWEEN THE MATHEMATICAL MODEL AND EXPERIMENTAL RESULTS

The stress-permeability model proposed above was used to construct a relation between the applied triaxial compressive stress levels and the corresponding change in coal permeability. To achieve this objective, the available test results have been used in conjunction with a weighted residuals procedure to determine the optimum values of the constants $C_o, \ldots, C_4$ in Eqn. (3), which minimize a summation of weighted squares of the residuals. An optimum value for the coefficient α in Eqn. (3) was determined by a trial and error procedure. Table (1) presents the present experimental results for various permeability tests and the corresponding maximum applied stress states. Figure (3) represents the mathematical correlation according to Eqn. (3) in K^*-E^* coordinates together with the present experimental results.

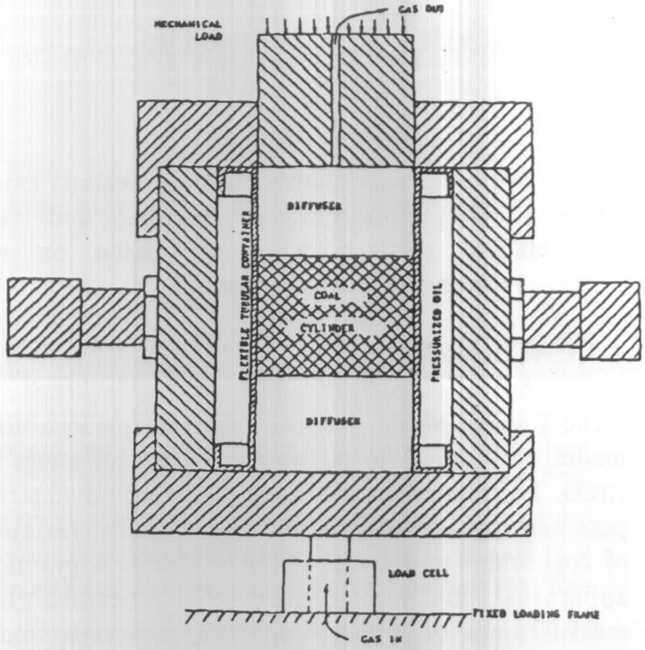

Figure 2. Hoek triaxial cell.

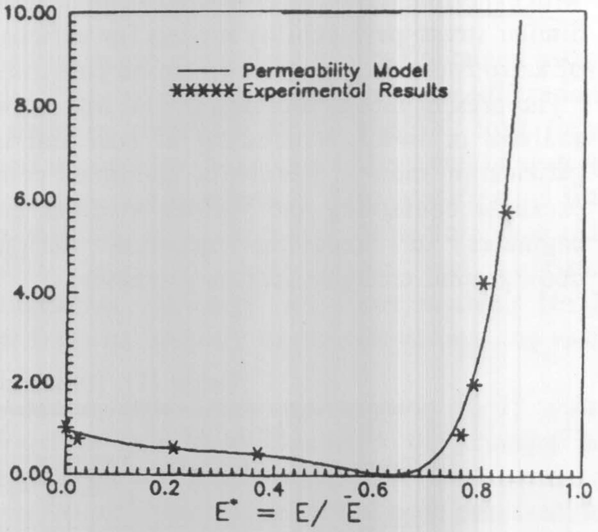

Figure 3. Correlation of permeability model with experimental results.

The present experiments were carried out using cylindrical specimens of a Nova Scotia coal. For this type of coal, σ_o=31.91 MPa and the optimum coefficients in Eqn. (3) have been determined to be:

$C_o = 0.9514147 \quad C_3 = -15.49672$

$C_1 = -3.729331 \quad C_4 = 0.0001604565$

$C_2 = 11.91620 \quad \alpha = 13$

Figure (3) indicates that a close agreement exists between the experimental results and the mathematical relation which is based on the proposed stress-permeability model.

4. CONCLUSIONS

The present work proposes a stress-permeability model for coal material under multiaxial states of stress. The model is based on a proposed novel stress parameter which governs the permeability variation of coal under multiaxial states of stress. A practical apparatus and procedure for permeability measurement of anisotropic rock materials under multiaxial states of stress is also presented. Comparison of results based on the proposed model with experimental results revealed a close agreement. Similar stress-permeability models for various types of anisotropic rock materials, can be constructed.

The present model provides a vital link between analyses of in-situ fracturing of coal and in-situ gasification models. Results of combined computer packages containing the various modules can aid engineers in achieving optimum designs of underground coal gasification processes. Development of such packages is currently under way at the authors' laboratories. Similar packages can be developed for optimization of enhanced oil recovery processes which require permeability enhancement of anisotropic rock formations such as oil, oil shale, and oil sand formations.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to Mr. D. Kuss for his performance in the experimental work. Financial support of this research by the National Sciences and Engineering Research Council of Canada is gratefully acknowledged.

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Table (1). Experimental Results for pemeability Tests

Test Number	Number of Specimens	Maximum Applied Stress State							Average
		σ_x	σ_y	σ_k	$\bar{\sigma}$	E	$\bar{E}$	k	k_f/k_t
1	-	0.14	0.14	0.14	0.118	0	1	0	1
2	3	0.68	0.14	0.14	0.2697	0.0230	1	0.0230	0.757
3	3	1.76	0.14	0.14	0.5730	0.2074	1	0.2074	0.580
4	2	2.30	0.14	0.14	0.7247	0.3688	1	0.3688	0.460
5	4	3.24	0.14	0.14	0.9888	0.7596	1	0.7596	0.880
6	4	3.51	0.14	0.14	1.0650	0.8976	1.144	0.846	1.965
7	4	3.78	0.14	0.14	1.1400	1.047	1.309	0.7998	4.24
8	4	4.32	0.14	0.14	1.2920	1.381	1.637	0.8436	5.73
9	5	5.67	0.14	0.14	1.6690	2.417	2.418	1.0000	46.64

Stresses σ_x, σy, σ_x have the unit of k_g/s_q. mm with σ_x acting along the axis of the cylindrical speclmens.