A methodology for hydrogeomechanical characterization of coalseam reservoirs

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ABSTRACT

The permeability of a coalseam reservoir is primarily due to impersistent natural joints or cleats. Coal strength and deformation behaviour is also due to the degree and orientation of the natural fracturing. Understanding and linking common parameters that control coal permeability, coal strength and coal deformation provides a common framework to evaluate well placement options for stability, initial permeability and changes in permeability due to coalseam reservoir operations. A hydrogeomechanical characterization methodology using the Geological Strength Index is presented along with a new approach to quantify the disturbance factor. This approach along with properties determined from well coal core sampling, well logging, well testing, and laboratory results allows for full coalseam reservoir evaluation regarding producibility and/or geological sequestration.

RÉSUMÉ

La perméabilité d'un réservoir d'houille ç'est premièrement á cause des joints où de fissures impersistants. La force et la comportement de déformation sont á cause du degré et de l'orientation des fractures qui occurrent naturellements. Une bonne compréhension et combinaison des paramètres communs qui contrôllent la perméabilité d'houille, la solidité d'houille, et la déformation d'houille, se donnent une structure pour bien évaluer les options pour placer des puits en connaissance de la stabilité, perméabilité intial, et de changements en perméabilité a cause des operations d'houille aux réservoirs. Ici on present une méthodologie pour la caractérisation hydro-géomechanical en utilisant le « Geological Strength Index » avec un nouveau méthod de quantifier le facteur de dérangement. Cette stratégie, informé par les samples de trognons d'houille, l'abattage des puits, tests de puits, et les résultats laboratoires, permèttent la pleine évaluation des réservoirs d'houille á propos de la productivité et/où d'autres séquestrations géologicales.

1 INTRODUCTION

Coal is a discontinuous organic rock mass generally consisting of two orthogonal major and minor joint sets (termed face and butt cleats respectively) perpendicular to the bedding plane which contains gas sorbed primarily in the intact matrix of coal. Initially mined for use as fuel, intensive research into the causes and mitigation of gas outbursts in coal mines led to the global development of commercial coalseam gas recovery, primarily CH_4, from deep unmineable coal seams. In Alberta alone, the natural gas from coalseams, or more commonly, coalbed methane (CBM) industry has gone from relatively little activity in 2002 (<100 wells drilled per year), to more than 3000 vertical and horizontal multilateral wells being drilled in 2005. Recent climate changes concerns, coupled with the preferential sorption of CO_2 over CH_4 in coal, has also made enhanced CBM (ECBM) recovery an attractive, yet unproven, value added option for potential coal seam sequestration operations.

1.1 Objective

Coal seam reservoirs are described as dual porosity matrix-cleat systems, where during production, gas desorbs from matrix micropore surfaces, is transported through the matrix to the cleat and bedding plane network and then to the well. The strength and deformation of the coalseam is also dependent on the cleat and bedding plane spacing. The orthogonal joint orientation of the joints leads to orthotropic deformation behaviour and anisotropic permeability. During production/injection process, changes in effective stress, gas content and gas composition leads to alterations in permeability.

The influence of the cleating and bedding planes, or jointing, stress and gas content/composition on the hydromechanical behaviour of coal has been well documented and numerical models have been developed to capture these behaviours. However, the testing methods used to determine input parameters are rarely representative of *in situ* conditions, and therefore the relationships derived from the data may not be valid under realistic reservoir life cycle operations.

Current field practices for reservoir CBM reservoir characterization presents difficulties to obtain relevant geotechnical data for full resource assessment and production forecasting. Core samples are usually extracted and partitioned for canister desorption testing, crushed for sorption isotherm measurements and analysed and burned for composition and rank measurements. Large (~200mm) intact cylindrical samples are generally not obtainable from coalseam sampling due to the friable nature of the coal, and samples which are obtained usually contain few fractures or are smaller core plugs which do not represent the highly permeable zones which is of primary interest in the coalseam reservoir.

New approaches to aid in CBM resource assessment and reservoir performance through inclusion of hydromechanical processes must fit with current characterization practices until advances become accepted in the CBM industry. The objective of this paper is to illustrate a workflow developed for the hydromechanical characterization of coalseam reservoirs linking coal mechanical and flow properties through a common geological index.

2 BACKGROUND

CBM reservoirs originate through a process termed coalification, in which plant material degrades diagenetically and metamorphically, resulting in two products: coal and methane gas (and trace amounts of other gases). Through geologic time, thermogenic degradation occurs as temperature and stress levels increase with increasing burial, increasing the carbon content and gas content of coal. A descriptive measure of the thermal maturity of coal is rank and in ascending order are: peat, brown coal/lignite, sub-bituminous coal, bituminous coal (high volatile, medium volatile, and low volatile), and anthracite. Coal seam reservoirs are typically sub-bituminous and above.

Naturally existing joints (cleats) are formed, although speculative as to the exact processes, from shrinkage, stress relief and extensional strain of the coal matrix during coalification (Labauch et al, 1998). Coal is very heterogeneous and its composition must be related to macroscopic, microscopic or submicroscopic scales of investigation. Macroscopically coal has four distinct bands or lithotypes, which have been related to the degree of cleating and thus correlated to higher or lowers permeability and/or stronger or weaker coalseams.

2.1 Coal as a Reservoir

Coalseams differ from conventional gas reservoirs in that the reservoir rock is not only the trapping mechanism but also the source of the gas. In the CBM reservoir, the reservoir rock is organic with micropore diameters from 5 Å to 50 Å in which the gas is stored through sorption. Under production gas moves by diffusion through the micropores to the much larger natural fracture system (cleats and bedding planes) and then flows through the fractures to the wellbore.

2.1.1 Gas Storage

Gas in coal is sorbed onto the coal micropore system existing in a condensed or liquid-like phase following a non-linear pore pressure volume relationship, typically represented by a Langmuir or extended Langmuir isotherm model. Moisture content, mineral matter and temperature have a negative effect on the volumes of gas a coal can store and there is little or no direct relation between gas sorption and coal rank (Bustin and Clarkson, 1998).

Reservoir gas contents are typically obtained by placing extracted core samples into sealed canisters and measuring gas volumes and desorption times. Sorption isotherms are typically determined by finely grinding coal particles (>0.5 mm diameter) and measuring increases in gas volumes with pressure.

2.1.2 Gas transport

The Gas Research Institute summarizes the accepted three step process model for gas transport during production. After a decrease in pressure due to initial production of gas and/or water contained in the cleats, gas molecules will desorb from the micropore surface of the matrix. Once existing as a free gas, gas molecules diffuse through the matrix from areas of high gas concentration to low concentration, and then enter the cleat system and flow to the well under Darcy flow (Figure 1). If coal is water saturated, water is 'pumped off' which creates a pressure gradient between the matrix and cleats. Therefore, in a CBM reservoir, the production of methane (or injection of CO_2) may be constrained by limitations in permeability or limitations in diffusivity.

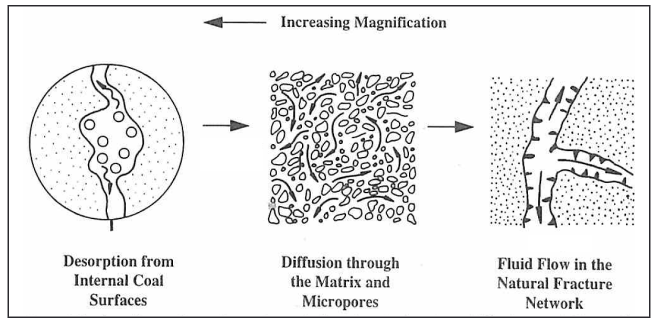

Figure 1. Idealized gas transport model of from gas desorption to diffusion through the coal matrix to flow into the cleat system (adapted from Gamson et al 1993).

2.2 Coal as a Structure

In current coal seam reservoir borehole stability studies and reservoir deformation models, the influence of cleats is generally not explicitly accounted for and a stress independent modulus is commonly assumed. Recent work has also attempted to link the Hardgroove index (a measure of fragmentation size) to rank, and then rank to UCS of coal (Figure 2). However the strength, and deformation, of coal is related to the joint spacing and/or size of specimen and the intact strength.

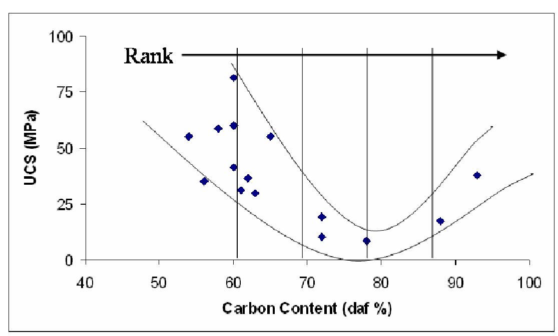

Figure 2. Relation of rank of coal to the UCS (adapted from Palmer et al, 2005).

The mechanical behaviour of coal has been widely studied for pillar design in coal mining and is therefore specific to those engineering design issues. Underground *in situ* testing showed the influence of sample size on strength, while large shear box testing and large simulated borehole testing showed the time dependent anisotropic strength and anisotropic deformation properties of coal. As is the case with rock masses, the degree jointing in coal also influences the strength and deformation behaviour of the coal mass.

2.2.1 Deformation

Coal exhibits non-linear deformation behaviour typical of rock masses where, as confining stress increases, modulus also increases. Although no specific testing has been conducted to directly investigating the influence of cleating on coal deformation, studies speculate that the cleating influences the non-linearity (Kaiser and Morgenstern, 1981). Furthermore, anisotropic testing on oriented coal samples revealed nonlinear anisotropic deformation, with the stiffness of the coal samples increasing normal to the bedding planes, normal to the major cleats, and normal to the minor cleats respectively. Due to the presence of joints which are typically spaced on the same order as the specimen for triaxial testing it is difficult to determine only the intact modulus of the coal, and therefore it is difficult to determine the shear and normal joint stiffness.

2.2.2 Strength

Bienawski (1964) showed the sample size dependency of coal strength and Medhurst (1996) developed a characterization method to capture the strength dependence as a function of lithotype and specimen size (Figure 3). This method related the brightness of the coal (an Australian measure of the lithotype) to the Hoek-Brown strength parameters, capturing the non-linear strength characteristics of coal. This was the first systematic attempt to relate common methods of cleat characterization in coal to strength characteristics for use in a failure criterion. The difficulty in coalseams comes when attempts are made at assessment of the intact properties of coal, as samples used for testing usually contain joints.

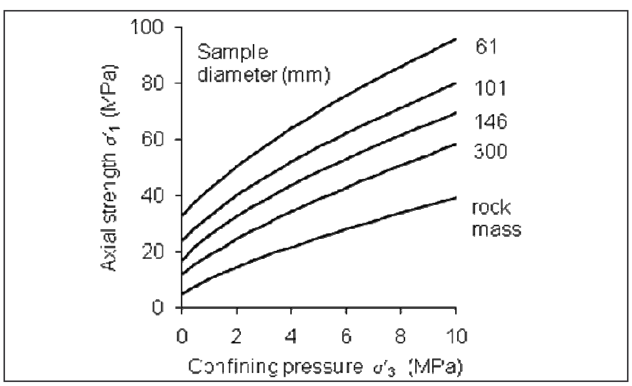

Figure 3. Hoek-Brown envelopes for 61mm coal core samples (adapted from Hoek and Brown 1997).

2.3 Coal Hydromechanics

The changes in effective stress, gas content, and gas composition (CH4/CO2 mixtures) are known to influence the hydrologic properties of coal. Coal has been shown to be effective stress sensitive and exhibits volume change as gas content and/or composition is altered, which in turn leads to strain in the coal mass, affecting permeability.

2.3.1 Effective Stress Sensitive Permeability

Patching (1964) initially showed the decrease in permeability from increases in isotropic effective stress and noted that changes in permeability, and the concurrent deformation associated with the isotropic stress increase, is time dependent. Many researchers have completed similar studies of confining stress or confining and deviator stress showing similar inverse relationships with permeability due to cleat aperture closure. Massarotto (2003) used a 'True Triaxial Coal Permeameter' cell to illustrate the influence of the principal stress orientation on the flow of gas in coal and the need to test coal at *in situ* reservoir conditions. The relative permeability of a coal is also stress dependent, although only one study on this has been published to date and trends are difficult to infer or apply.

2.3.2 Deformation Due to Gas Content/Composition

Volumetric change of coal due to changes in gas volumes has been investigated in the laboratory and speculated to be experienced in the field. Siemons et al. (2004) showed that for some basins, CO_2 may be preferentially sorbed over methane and that each coal basin may need to be investigated individually. Sabir (2003) showed the different sorption behaviours between an intact coal under an isotropic stress and the same crushed coal sample. The intact sample under stress sorbed less CO_2 and the isotherm model was a different shape than that of crushed sample. Robertson and Christiansen (2007) showed that modeling of laboratory results for swelling due to CO2 injection in coal under stress improved if a term accounting for the effective stress were included.

3 RESERVOIR CHARACTERIZATION

The hydrological, mechanical and hydromechanical properties described above are required to make sound decisions when assessing/planning the development of a coalseam reservoir. Using a classification method which enables consistent evaluation of each parameter creates a platform to make those decisions. Figure 4 shows an idealized coalseam and the transition from an intact scale to a heavily jointed scale of evaluation. The intact scale samples may be acquired from core sampling and used in laboratory testing to obtain coalseam properties. The properties obtained from the testing will not be representative of the heavily fractured scale behaviour of the coalseam, and therefore will need to be adjusted.

Several Rock Mass Classification (RMC) systems have been developed to account for the influence of fractures on the strength and deformation of the rock mass. Below outlines the use of the Geological Strength

Index (*GSI*) RMC system to characterize the mechanical and hydromechanical behaviour of a coalseam. The *GSI* classification system is advantageous due to the ability to scale the strength and deformation results obtained from laboratory testing to field scale using a single common index.

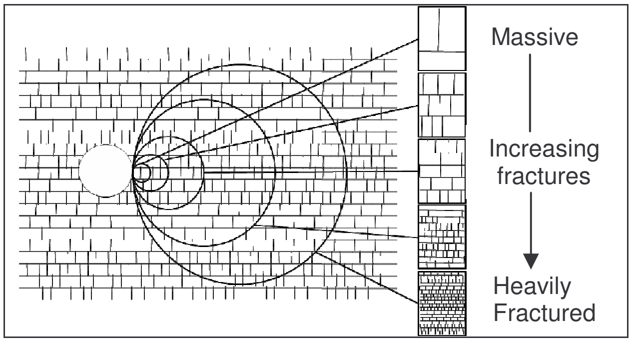

Figure 4. Idealized coalseam with a borehole showing the transition from an intact or massive sample to a heavily jointed sample (modified from Hoek and Brown, 1997).

3.1 Coalseam Sampling

The difficulties encountered when sampling a coalseam downhole result from the friable nature of the coal itself. Generally the portion of the coal seam which is recovered is the competent non jointed portion of the coalseam. The sampled fractured component of the coalseam is recovered as rubble. The intact core recovered contains little or no jointing therefore laboratory permeability measurements underestimate the in situ coalseam permeability. The strength and deformation results from the intact core also over estimate the in situ behaviour. Therefore using the data which can be obtained from laboratory testing requires adjustment to the field scale.

3.2 Geological Strength Index

GSI was first introduced by Hoek (1994) as a method to degrade the intact strength of a rock to in situ rock mass strength. *GSI* is assigned to a rock mass through visual comparisons of blockiness and joint surface conditions (Figure 5). The estimation or evaluation of *GSI* is then used to predict/estimate deformation and strength reduction of a rock mass from intact rock behaviour measured in the laboratory.

3.3 Deformation

The Young's modulus of a rock mass (E_{RM}) is function of the modulus of the intact rock (E_i) and of the fracture spacings and fracture stiffness. Hoek and Diederichs (2006) developed an expression relating *GSI* and a disturbance parameter, *D* to define a Young's modulus reduction ratio (E_{RR}) (Eq 1) and is plotted in Figure 6.

$$E_{RR} = \frac{E_{RM}}{E_i} = 0.02 + \frac{1 - D/2}{1 + \exp\left[(60 + 15/D - GSI)/11\right]} \quad [1]$$

The parameter *D* was introduced as a method to characterize the disturbance of the rock mass from excavation method and varies from 1.0 to 0.0 for highly disturbed to undisturbed rock masses. The authors give guidance on the selection of *D* stating that *D* of the rock mass will decrease moving away from the excavation face. It is proposed here that this distance is related to the confining stress state of the rock mass, and therefore *D* is a function of the confining stress. For coal it is possible to test samples containing jointing and therefore develop a function for *D* which relates it to the confining stress.

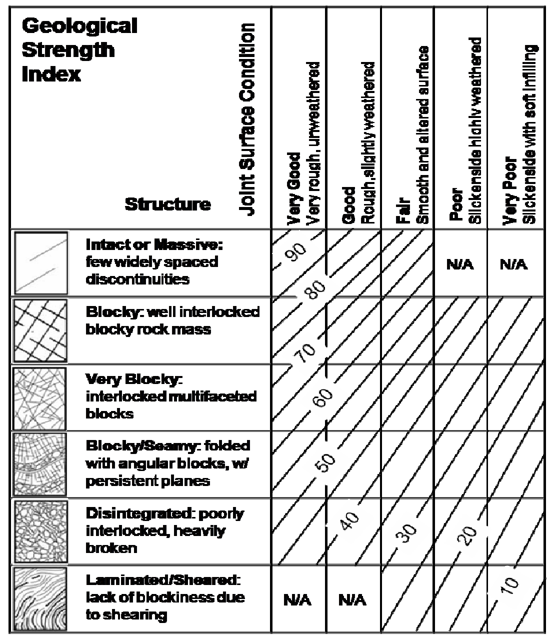

Figure 5. Relation between the structure and joint surface conditions for a rock mass and the associated value for GSI (adapted from Marinos et al, 2006).

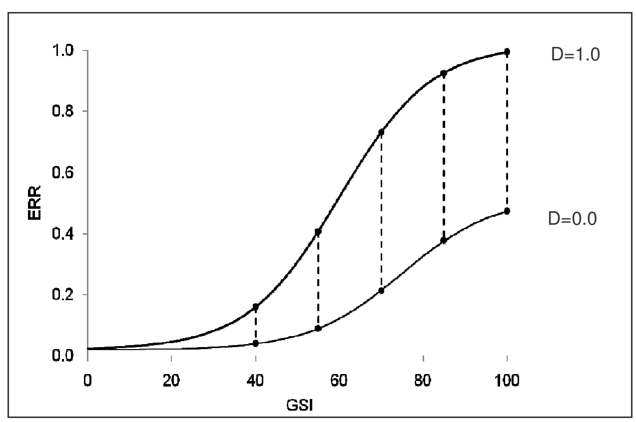

Figure 6. The plotted function of the Young's modulus reduction ratio using *GSI* and *D*.

Laboratory measurement for *E* versus confining stress from coal specimens containing joints and a specimen scale value of *GSI* are required to establish the boundary values for the proposed function. When *D*=1.0, E_{RR} is a minimum (E_{RR1}), and when *D*=0.0, E_{RR} is a maximum (E_{RR0}). Assuming that *D*=1.0 corresponds to a confining stress equal to zero, and *D*=0.0 corresponds to the confining stress where E_{RM} does not increase. The values of *E* between these end points can be used to establish the shape of the curve with Eq 2. *D* is assumed to vary exponentially with confining stress and takes the form of Eq 3 with a fitting parameter *h* having the units Pa^{-1}.

$$ERR = ERR_1 + (ERR_0 - ERR_1)(1 - D) \quad [2]$$

$$D = \exp[-h\sigma_3'] \quad [3]$$

Using this technique may be problematic as the values for *E* should be obtained from the same specimen as the values for *GSI* on a small scale specimen to specimen basis may change slightly. Maintaining consistency may be accomplished through static (loading) or dynamic (velocity) modulus testing at various confining stresses.

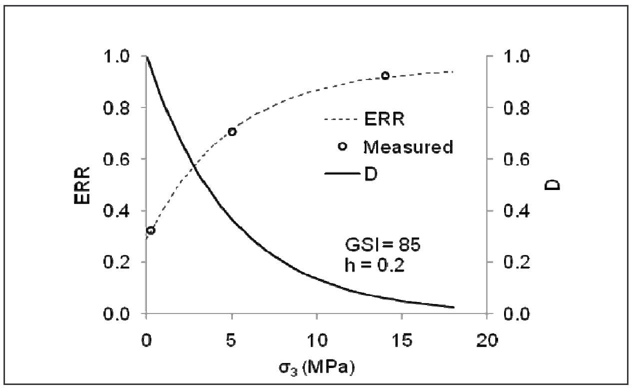

Figure 7. Plot of fitted Eq 6 and Eq 7 for a coal sample with a GSI=85.

3.4 Strength

The Hoek-Brown (H-B) failure criterion has been developed specifically to capture the nonlinear behaviour of rock and rock masses. The H-B parameters are determined from curve fitting laboratory test data to Eq 4.

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(\frac{m\sigma_3'}{\sigma_{ci}} + s\right)^a \quad [4]$$

The intact unconfined compressive strength is denoted σ_{ci}, where m_i, s_i, and *a* are intact rock properties analogues to cohesion and friction. The intact H-B parameters can then be adjusted to the rock mass scale (*RM*) using *GSI* and *D* through Eqs 5, 6, and 7, and can be incorporated into Eq 1 for field scale applications.

$$m_{RM} = m_i \exp[(GSI - 100)/(28 - 14D)] \quad [5]$$

$$s_{RM} = s_i \exp[(GSI - 100)/(9 - 3D)] \quad [6]$$

$$a_{RM} = 1/2 + 1/6[\exp(-GSI/15) - \exp(-20/3)] \quad [7]$$

As noted above, obtaining coal samples which contain no jointing is difficult and consequently the intact H-B parameters cannot be directly obtained. One solution is to subsample the retrieved core to a size that does not contain fractures. A second technique used by Gentzis et al (2007) was to characterize the fracturing using *GSI* before testing and fit *GSI* adjusted parameters to the laboratory data, and then back calculate the intact values. This technique may also become problematic as each coal sample tested must have the same values of *GSI*. If they do not have the same *GSI* more coal samples will need to be tested and an optimization technique used to fit the H-B parameters.

3.5 Diffusion and Desorption

Measurements for total gas content and diffusion times are made on recovered core samples placed in canisters at the core site. Desorption isotherms are determined from core samples which are crushed to a 200 sieve size and then the total gas sorbed verses the gas pressure is measured. In both cases the diffusion and desorption behaviours of the coal are not characterized under in situ conditions.

The influence of stress on diffusion kinetics and sorption/desorption isotherms is not well understood. However there is sufficient evidence that stress does influence each of these reservoir properties, and that laboratory testing as close to reservoir conditions is required. Functions which relate the observed behaviours as a function of stress and possibly other parameters may then be incorporated to account for the behaviour and to assess their impact on reservoir performance.

3.6 Permeability

As stated above the permeability measured from laboratory samples generally underestimates the coalseam's in situ permeability. This is due to the unrepresentative nature of the laboratory specimen when compared to the entire coalseam. In situ permeability measurements from well testing may be more representative provided that the analysis of the results takes into account the geomechanical effects on fracture opening or closure during pressure build up and draw down. Laboratory permeability measurements under varying effective stress conditions on specimens which contain fractures may be used to determine the stress sensitivity of the coalseam provided stress change in conditions which closely simulate field conditions are used.

Relative permeability results from laboratory testing are useful if the test specimen contains jointing. Also if measurements are completed at different effective stress conditions, the stress dependent relative permeability characteristics of the coalseam may become better understood.

3.7 Strain Dependent Permeability

Several formulations and approaches have been developed to account for the influences of changes in effective stress on changes in permeability in coalseams. Figure 8 shows an idealized representation of a coalseam with persistent fracturing in the directions *i*, *j*, and *k* which represent directions *x*, *y*, and *z* respectively. The permeability of a coalseam in any direction at any effective stress state (K_i') can be expressed as the summation of the initial aperture (b_i) at an initial effective stress state, and the change in aperture (Δb_i) due to the change in effective stress state for each of the fractures sets (s_i) contributing to the flow (Eq 8). Therefore correctly accounting for the strain occurring in the apertures due to the change in stress is important (Gu and Chalaturnyk 2006, Chen et al 2007).

$$K_i' = \frac{1}{12}\left[\frac{(b_j + \Delta b_j)^3}{s_j} + \frac{(b_k + \Delta b_k)^3}{s_k}\right] \quad [8]$$

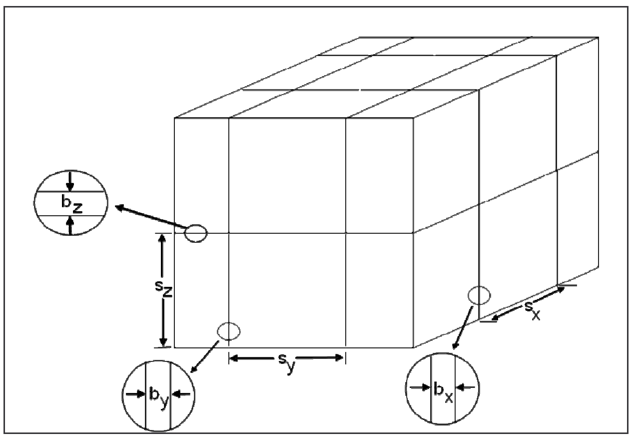

Figure 8. Idealized coal block showing persistent fracturing in the *x*, *y*, and *z* directions along with fracture spacings (*s*) and fracture apertures (*b*)

Deisman and Chalaturnyk (2008) have modified an approach from Lui et al. (1999) using the E_{RR}, partitioning the change in normal strain of the coalseam ($\Delta\varepsilon_{RM,i}$) to changes in fracture aperture ($\Delta\varepsilon_{b,i}$) and change in matrix strain through Eq 8. A similar approach is followed for change in shear strain ($\Delta\gamma_{RM,ij}$) occurring in the coalseam and change in fracture length (Δl_{ij}) Eq 9. G_{RR} is the shear modulus reduction ratio and as there is no guidance on its selection an assumption must be made.

$$\Delta b_{n,i} = s_i \Delta\varepsilon_{RM,i}(1 - E_{RR}) \quad [9]$$

$$\Delta l_{ij} = s_i \Delta\gamma_{RM,ij}(1 - G_{RR}) \quad [10]$$

The change in aperture is assumed be a combination of the effects of displacement normal to the aperture (ΔN_i) and the dilation effects due to shear displacement in both directions perpendicular to the aperture (ΔS_{ij} *and* ΔS_{ik}) (Eq 11).

$$\Delta b_i = \Delta N_i + \Delta S_{ij} + \Delta S_{ik} \quad [11]$$

The normal aperture change is calculated from the initial aperture and the portion of the total change in normal rock mass strain occurring in the fractures (Eq 12). The component of aperture change due to change shear strain is found from a combination of the fracture spacings (s_i), the total shear strain occurring in the rock mass perpendicular to the fracture of interest, and the dilation angle (d_{ij}) of the fracture (Eq 13).

$$\Delta N_i = s_i \Delta\varepsilon_{i,RM}(1 - ERR) \quad [12]$$

$$\Delta S_{ij} = s_i \Delta\gamma_{RM,ij}(1 - GRR)\tan(d_{ij}) \quad [13]$$

Several assumptions are made in this formulation which includes the immediate mobilized shear dilation angle. This is known to be false as laboratory results indicate that coal samples will contract before they dilate and a minimum amount of strain is required before dilation occurs. It is also assumed the dilation occurring in either perpendicular direction is independent of the total shear displacement which has already occurred. It is also assumed that there is no difference between the hydraulic aperture and the mechanical aperture, and therefore the roughness of the fracture surface does not influence the fluid flow.

4 CBM FIELD APPLICATION

Once a coalseam reservoir has been identified for possible development the first step is generally to drill a well to determine reservoir properties through well logging, well testing and core samples for lab testing. The following demonstrates a CBM reservoir mechanical and hydromechanical characterization using some assumptions and published data from Gentzis et al (2007) in which testing on six different coalseams was completed.

4.1 Core sampling

Coal samples recovered from the coalseam are either intact with few joints, heavily jointed, or rubble. These are used to determine the coalseam gas content and desorption times by immediately placing inside desorption canisters at zero effective stress. Figure 4 can be used to aid in scale reference (drawing in the correct joint spacing for the specific coal sample) and using a rating of fair for coal joint surfaces in the *GSI* diagram (Figure 5), a value/range for *GSI* can be selected before the coal is placed inside the canisters. Gentzis et al reports values of *GSI*=85 for all of the samples tested from each of the six coalseams.

4.2 Well Logging

A suite of well logs are typically run once the well is drilled and/or completed. Logs which are useful for estimating hydromechanical reservoir properties include the density, sonic and Formation MicroImager (FMI) logs. The velocity obtained from the sonic log in combination with the density log can be used to calculate the reservoir shear and bulk modulus, while the FMI log can be used to determine joint spacings, trace lengths and apertures particularly in the regions in which intact core recovery was not possible.

With joint spacings and trace lengths obtained for the full dimension of the well, a realistic picture of the coalseam and joint spacings can be developed similar to Figure 4. Using the picture of the coalseam along with the *GSI* diagram, a value for *GSI* can be selected for the coalseam scale. In this case an average, in all three directions, a joint spacing of 5 cm is assumed for each coal seam which gives a *GSI* between 45 and 50.

4.3 Well testing

Well tests are used to determine reservoir pressure and reservoir permeability through pressure build up, draw downs and shut in tests. Although coalseam reservoirs are known to have anisotropic permeability, determining these values from a single well is complex. Typically a single value or horizontal and vertical permeabilities are reported. For the testing completed by Gentzis et al, coalseam permeabilities were not reported, therefore an isotropic value of 10 md is assumed.

4.4 Laboratory Testing

Triaxial testing on the retrieved coal core samples to obtain reservoir properties should be completed at reservoir effective stress and temperature conditions. Isotherm, desorption time and shrinkage/swelling behaviours are not measured at these conditions due to the time lengths required, however the results may be more indicative actual CBM reservoir behaviour.

Gentzis et al. (2007) report axial strength and Young's modulus on three different samples at different confining stresses from each of the six sampled seams. All of the testing was completed on large borehole size samples. If the samples were required to be sub-sampled to create cylindrical specimen for triaxial testing, an estimate of *GSI* would be required for each sample in order to relate the measured strength values to each other.

Using the reported *GSI* values for the samples the values for *h* were established for each of the coal seams as well as the back calculated E_{in}. Table 1 lists these results along with the reported intact σ_{ci} and m_i for each of the coalseams. The predicted versus measured values of E_{RM} using the Eq 1 and Eq 3 are shown in Figure 9.

The predicted E_{RM} results agree well with the measured results at higher values however did not predict the lower values well. The reported values of *GSI*=85 is suspect, and as no photographs of the samples are available, it was decided to alter the values within a reasonable range to achieve a better fit of predicted versus measured E_{RM}, acknowledging that it is only a curve fitting exercise without inspection of the coal samples. The values of GSI selected were between 77 and 95 while keeping the remaining values unchanged, which results in a better fit to the data (Figure 10).

Table 1. Reported results from Gentzis et al (2007) for back calculated Hoek-Brown parameters, back calculated intact modulus and the parameter *h (GSI*=85*)*

Sample	σ_{ci} (MPa)	m_i	E_{in} (GPa)	h (Pa^{-1})
GH3	17.0	15.2	3.44	0.2
GH7	45.5	6.2	3.40	0.27
GH10	42.3	19.0	4.92	0.4
8UX	29.2	16.9	4.86	0.4
ELK	56.8	6.0	5.47	0.8
CR	39.7	6.7	4.43	0.5

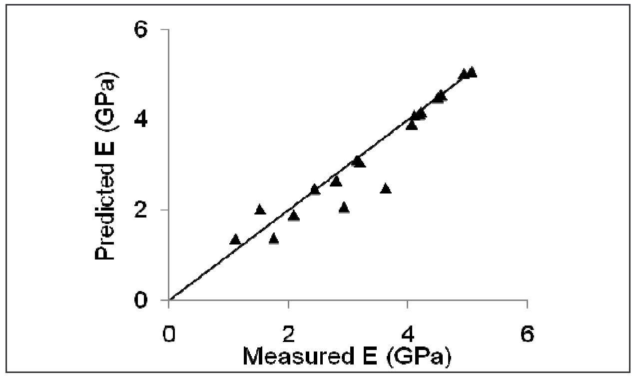

Figure 9. Predicted verses estimated values of rock mass modulus E_{RM} for the coalseams reported by Gentzis et al. The value of *GSI* was 85 for each of the samples.

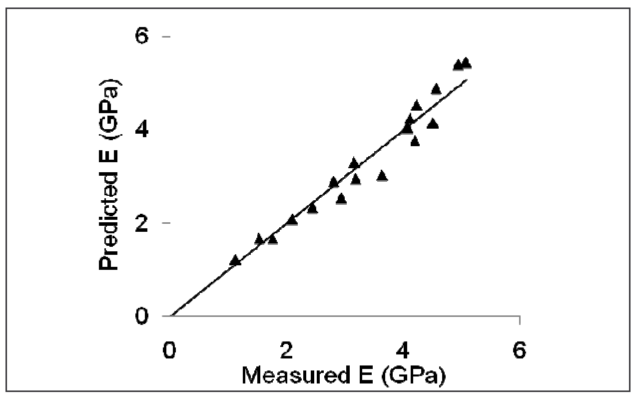

Figure 10. Results from adjusted *GSI* values for predicted verses estimated values of E_{RM} for the coalseams reported by Gentzis et al.

5 CONCLUSIONS

A methodology to characterize the mechanical and hydromechanical properties of a coalseam reservoir has been demonstrated. The importance of testing for reservoir properties at reservoir conditions is discussed especially when testing for behaviours which may be stress sensitive such as isotherm and desorption behaviours. *GSI* approach allows for a consistent approach to scale the strength and deformation properties from a laboratory scale to a borehole scale and to a coalseam scale. With the addition reservoir properties obtained from well testing and well logging, the information can be integrated for use in mechanical and hydromechanical analysis.

It is illustrated above that accurate ranges of *GSI* are required to reasonably estimate the coalseam modulus which requires experience. Eq 1 was also developed using data from hard rock experiments and may be refined for coal, however it does predict coal behaviour reasonably well. The development of the confining stress dependent deformation function also requires further comparison versus laboratory data and possibly refinement.

6 ACKNOWLEDGEMENTS

The authors would like to thank Dr. Jamie Jimenez for his endless critiques as well as the insights offered by Professor C. Derek Martin.

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