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Laboratory studies of the compressibility and permeability of low-rank coal samples from the Powder River Basin, Wyoming, USA

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ABSTRACT: We characterize the mechanical properties of coal samples from the Powder River Basin (Wyoming, USA) by conducting laboratory experiments. We present results from laboratory measurements of adsorption, static and dynamic elastic moduli, and permeability as a function of effective stress, pore pressure, and gas species. Notably, we observe that CO_2 adsorption causes the static bulk modulus to decrease by a factor of two, while the dynamic bulk modulus remains essentially unchanged. Permeability of both intact and powdered samples decreases by approximately an order of magnitude in the presence of CO_2, which is consistent with observations of adsorption-related swelling of the coal matrix. Interestingly, CO_2 appears to change the constitutive behavior of coal; Helium saturated samples exhibit elastic behavior, while CO_2 saturated samples exhibit viscous, anelastic behavior, as evidenced by creep strain observations.

1. INTRODUCTION

Coal bed methane (CBM) production from unmineable coal seams is considered to be an unconventional gas resource; methane is typically generated during the coal maturation process and resides in the coal matrix as an immobile, adsorbed phase. During CBM production, the pressure inside a coal seam is reduced and methane desorbs from the coal matrix, at which point it exists as a free gas and can flow through the cleat (natural fracture) system to the producing wells. According to the U.S. Energy Information Agency (EIA), coal bed methane production currently accounts for 10% of the domestic natural gas supply, and is anticipated to increase significantly over the next several decades as conventional gas supplies continue to decline [1].

Coal exhibits the interesting property of selectively adsorbing certain gases. In particular, many coals have been observed to preferentially adsorb carbon dioxide over methane [2], making coal an attractive candidate for geological sequestration of CO_2, since adsorbed gases are essentially immobile [3,4]. In addition, because the adsorption of carbon dioxide forces desorption of methane, it is possible that CO_2 can be used to enhance coal bed methane (ECBM) production [5-7].

While several small-scale field studies have been performed or are currently underway in various coal seams around the world [8-11], the feasibility of ECBM or geological sequestration of CO_2 for a given site is still largely dependent on predictions from numerical modeling tools such as reservoir simulators that have been modified for CBM [12,13]. These numerical models require values for numerous input parameters, many of which can be derived from laboratory data.

Furthermore, predictions from reservoir simulators can only be as accurate and realistic as the underlying theoretical and mathematical models allow. Laboratory studies are needed to develop and verify theoretical models of the complex mechanical and chemical behavior of coal. For example, the adsorption of gases onto the surfaces of the coal matrix has been observed to cause volumetric swelling of the coal, while desorption of gases causes volumetric shrinkage [14,15]. This swelling and shrinkage of the matrix changes the width of the cleats and natural fractures in the coal, which in turn causes changes in cleat permeability [16,17,18]. Because adsorption, and therefore swelling, increases with pressure, permeability is expected to decrease as a function of pressure. However, in the absence of swelling, permeability will increase as a function of pressure. These opposing effects need to be better understood if accurate models of permeability change are to be developed for coal.

The Power River Basin, which extends from eastern Wyoming into southeastern Montana, is the largest and fastest growing CBM producer in the world, with approximately 17,000 wells currently producing 30 billion cubic feet of gas per month [19]. The primary production coal seams fall within the Wyodak-Anderson zone of the Fort Union Formation, at depths ranging from 500 to 1500 feet. For this study, we obtained four-inch diameter core samples from the Roland and Smith coal zones, from a depth range of 1300-1400 feet. The samples have an initial porosity of approximately 10%, an initial permeability of 1 millidarcy, and and ash content that varies from 10-20%.

Our research focus for this study has been to better understand the effects of adsorption on the mechanical and flow properties of sub-bituminous coals. We conducted laboratory experiments on one-inch diameter core samples of coal, under hydrostatic and triaxial loading conditions, as a function of effective stress, using both helium and carbon dioxide as saturating gases. We present measurements of elastic stiffness, permeability, swelling strain, and creep strain, for both intact and powdered coal samples.

2. SAMPLE DESCRIPTION AND EXPERIMENTAL PROCEDURE

We obtained 4-inch diameter core samples of sub-bituminous coal from the Roland and Smith coal zones of the Fort Union Formation in the Powder River Basin, Wyoming. The depth to these zones is approximately 1300-1400 feet. Note that these samples are from the same well and depth range as those reported on by Tang *et al* [20]. Figure 1 shows the field area, and Figure 2 shows the stratigraphic column. These samples were stored at room conditions, and so it was assumed that the initial methane gas was completely desorbed prior to testing. Due to the numerous cleats and micofractures, obtaining one-inch diameter core plugs for testing was difficult, and some samples were molded from powdered coal. For both the intact and powdered coal samples, sample preparation procedures followed those described by [20] in an effort to make comparison of the two data sets possible.

For both the intact and powdered samples, cylindrical core plugs were prepared, with a nominal size of one-inch diameter and two-inch length. For reference, the initial porosity of the intact samples was approximately 10%, while that of the molded samples was approximately 30%. The samples contain 10-20% ash content, which serves to reduce the initial bulk density (~1.5 g/cc for the intact samples). Prior to testing, all samples were vacuum-dried until constant mass was achieved, to remove residual moisture and gas.

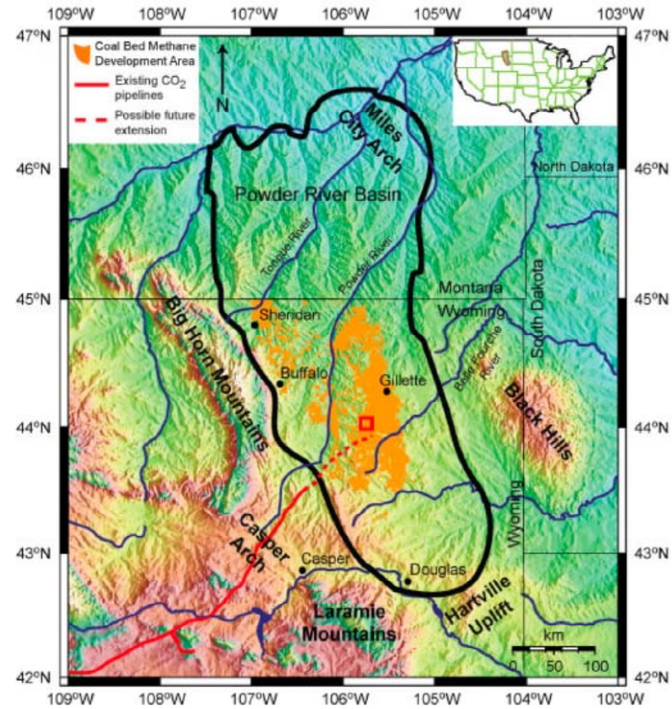

Figure 1: Topographic map of the Powder River Basin, showing the area of active CBM development (adapted after [21]).

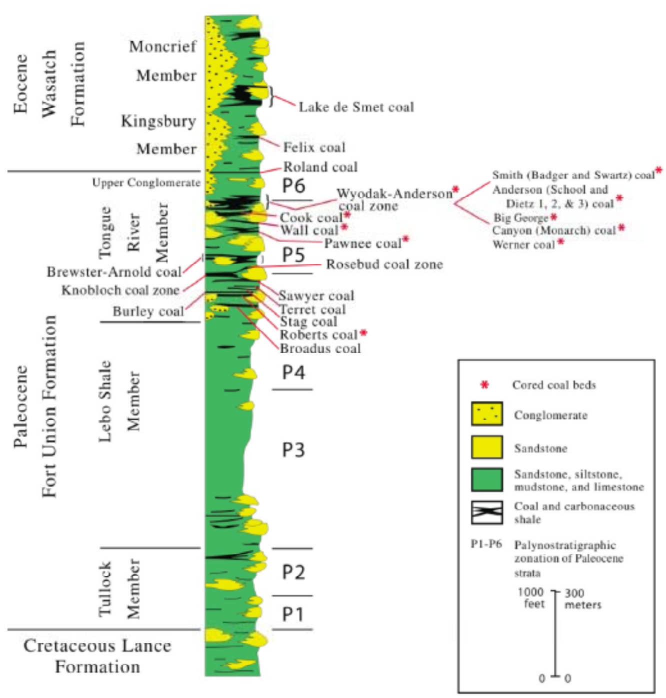

Figure 2: Stratigraphic column of the major formations and coal zones of the Powder River Basin (adapted after [19]).

Our laboratory apparatus is a conventional triaxial machine, commonly used in rock mechanics testing. For the purpose of this study, we modified it to enable simultaneous measurement of stress and strain, ultrasonic P and S wave velocities, and gas permeability. For schematics and specific details concerning the apparatus, please consult the 2006 GCEP Annual report (http://gcep.stanford.edu/).

In an effort to establish a baseline set of measurements, we tried to isolate the effects of stress, pore pressure, temperature, moisture, and gas mixture by varying only one component of the system at a time. For all of the data shown below, measurements were carried out at room temperature, only single phase Helium or CO_2 was used as a pore fluid, and moisture and humidity were minimized. However, both pore pressure and effective stress were varied during experiments. Measuring permeability as a function of both pore pressure and effective stress is particularly important, as permeability can vary due to swelling/shrinkage (a function of pore pressure) and due to mechanical opening/closure of pathways (a function of effective stress).

3. ADSORPTION ISOTHERMS

We measured adsorption isotherms for both intact and powdered coal samples. Total adsorption isotherms (at 22°C) were determined for pure CO_2 using the volumetric method. Our results are shown in Figure 3. While our isotherms fall slightly below those reported by Tang *et al* [20], given the difference in apparatus setups and innate heterogeneity of coal, we believe that a maximum of 15% error between the data sets provides a satisfactory match.

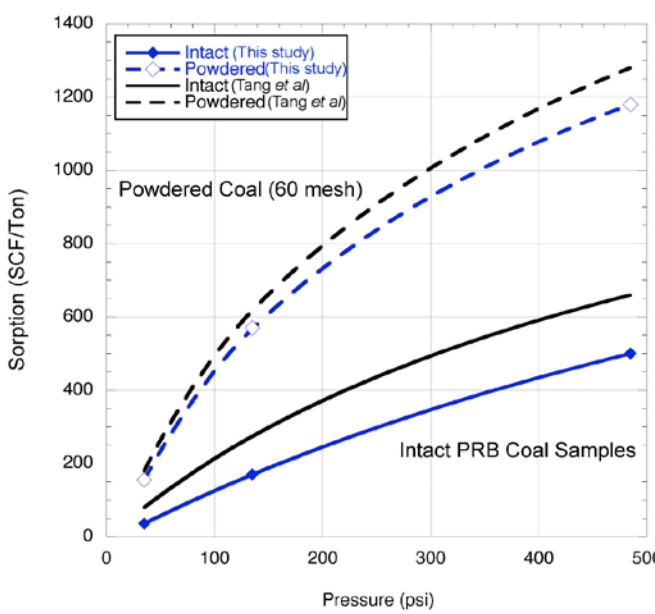

Figure 3: Total adsorption isotherm for powdered and intact coal samples from the Powder River Basin, Wyoming. Experiments performed at a temperature of 22 C. Blue curves show data from this study. Black curves are shown for comparison, and are adapted after [20].

4. STATIC AND DYNAMIC ELASTIC PARAMTERS

We measured the elastic stiffness of intact samples of PRB coal using two different methods. Static elastic parameters can be determined from a stress-strain curve. In general, the slope of the tangent of the stress-strain curve at a particular value of strain gives the elastic stiffness at that point. For example, bulk modulus can be calculated by plotting hydrostatic stress against volumetric strain. On the other hand, assuming that the sample is an isotropic, homogeneous medium, dynamic elastic parameters can be derived from measurements of ultrasonic velocities. At a particular value of stress or strain, the dynamic bulk modulus is given by:

$$K = \rho\left(V_p^2 - \frac{4}{3}V_s^2\right), \quad (1)$$

where K is the bulk modulus, ρ is bulk density, Vp is the P-wave velocity, and Vs is the S-wave velocity. Note that for an isotropic, homogeneous elastic material, the static and dynamic measurements will produce identical values of bulk modulus.

For these tests, a series of loading cycles were performed, in which the confining pressure was increased to a target pressure at a rate of 6 MPa/hour, held constant for a period of 10 hours, and then decreased back to the initial pressure value. The pressure holds were used to test whether or not creep strain would occur; please see the section on creep strain below. Pore pressure was held constant during these tests. The samples were first saturated with Helium, and a series of loading cycles was performed. The samples were then unloaded to the initial conditions, and saturated with CO_2. The same series of loading cycles was then repeated. Stress and strain data were collected every 10 seconds. P and S wave velocities were captured every 60 seconds.

The results from these measurements are shown in Figure 4. There are several important details to note in this Figure. First, note that for the Helium-saturated case, the dynamic and static values of bulk modulus are nearly identical, indicating that the coal sample is elastic, which is the expected behavior. Interestingly, when the same sample is saturated with CO_2 the static bulk modulus decreases by approximately a factor of two, while the dynamic modulus increases only slightly. This divergence in behavior suggests that the CO_2 is bearing some of the externally applied load, and is stiffening micropores while lubricating larger grain and maceral boundaries.

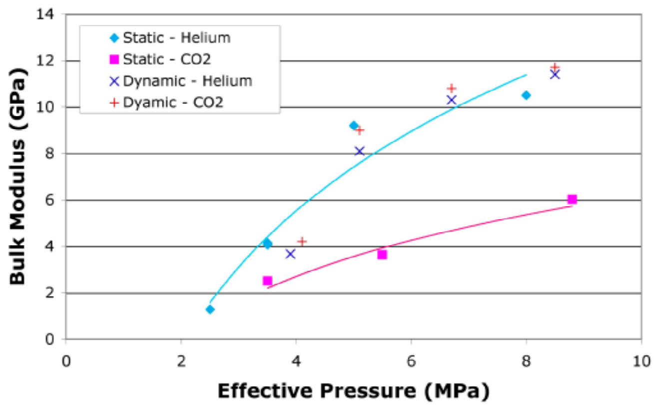

Figure 4: Static and dynamic bulk modulus plotted as a function of effective pressure for Helium and CO_2 saturated PRB coal samples. The pore pressure was kept constant at 1 MPa. Note that while the static bulk modulus decreases by a factor of two after being saturated with CO_2, the dynamic bulk modulus actually increases slightly.

5. PERMEABILITY OF INTACT AND POWDERED PRB COAL SAMPLES

Klinkenberg-corrected measurements of Darcy-flow permeability are plotted as a function of effective stress in Figure 5. Please note that unlike most gas permeability measurements on coal, for these tests the pore pressure was held constant at 1 MPa, while the effective stress was increased. We implemented this experimental procedure because we are interested in understanding the effects of both adsorption and stress on permeability.

There are several things to note in Figure 5. For the reference data set collected using Helium, the observed decrease in permeability with increasing effective stress can be attributed to the mechanical closing of cleats and other pathways. Saturating the samples with CO_2 causes a decrease in permeability, regardless of effective stress, and can be thought of as a downward shift along the y-axis in this plotting space. Finally, the differences between the powdered and intact samples are interesting. Relative to the intact sample, the powdered sample has a higher initial permeability, a larger change in permeability with increasing effective stress, and a smaller decrease in permeability following CO_2 saturation. All of these observations are consistent with the fact that powdered sample has more porosity (30% vs. 10%) and is more compressible (by a factor of 2-3) than the intact sample.

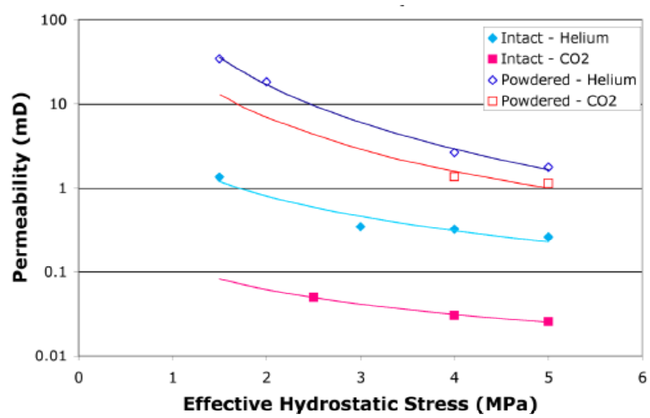

Fig. 5. Gas permeability plotted as a function of effective hydrostatic stress for both powdered and intact PRB coal samples.

6. MEASUREMENTS OF CONFINED SWELLING STRAIN

The decrease in permeability following CO_2 saturation suggests that the coal matrix is swelling in response to adsorption. Because we have been measuring permeability under hydrostatic loading conditions, we elected to measure volumetric swelling strain under the same boundary conditions, in an effort to make relating the two quantities easier. These swelling measurements are shown as a function of time in Figure 6, and as a function of pore pressure in Figure 7. In both figures, the effective hydrostatic stress is held constant at 1 MPa.

The swelling behavior as a function of time is interesting because the swelling strain can be seen to increase linearly at first, followed by a much more gradual asymptotic approach to the equilibrium swelling for a given pore pressure. These observations can be attributed to convective behavior while the CO_2 is saturating the macro-pore space and cleats, followed by diffusive behavior as the CO_2 slowly invades the matrix. As expected, swelling strain increases with adsorption, which in turn increases with pore pressure. While we do not currently have enough data to attempt any quantitative modeling of the adsorption and swelling, we plan to continue making swelling measurements in the future.

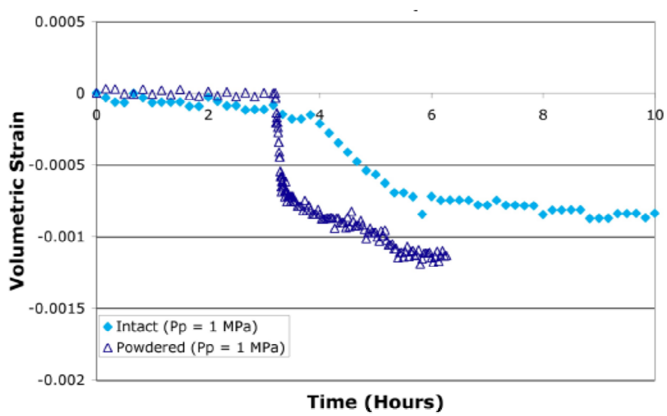

Figure 6: Volumetric swelling strain plotted as a function of time for powdered and intact PRB coal samples. Negative strain indicates swelling. The samples are initially saturated with Helium. At approximately 3 hours, the samples are flooded with CO_2 at constant pore pressure and effective hydrostatic stress.

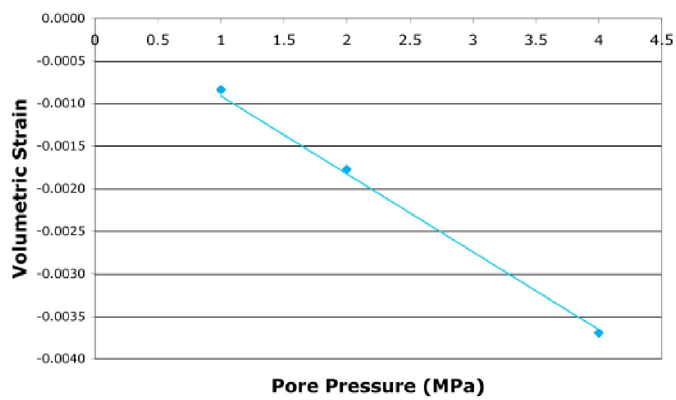

Figure 7: Volumetric swelling strain plotted as a function of pore pressure for intact PRB coal samples, at a constant effective hydrostatic stress of 1 MPa. The increase in swelling with pore pressure appears to be linear, but more data at higher pore pressures are needed to confirm this.

7. OBSERVATIONS OF CREEP STRAIN

During the cyclic-loading tests we conducted, we observed an interesting change in deformation behavior when the samples were saturated with CO_2. Specifically, even when the effective hydrostatic stress was held constant, the samples continue to deform. This time-dependent behavior is typical of materials that have a viscous component of deformation. It is possible that this is a manifestation of coal plasticization at low temperature. Considerable work needs to be done to further understand this phenomenon. Our results to date are shown in Figure 8.

8. DISCUSSION

The key advantage to sequestering CO_2 in coal beds over other geological storage options lies in how the CO_2 is stored after injection. Because CO_2 is stored by being adsorbed onto surfaces within the coal matrix, it offers the possibility of permanent storage. In addition, CO_2 has a higher adsorptive selectivity than methane, which leads to the possibility of injecting CO_2 to displace methane and enhance coal bed methane production. However, adsorption causes swelling of the coal matrix, which may cause a loss of permeability. This decrease in permeability has been observed in small-scale pilot studies at RECOPOL [8] and Yubari [9] as a loss of injectivity near the wellbore. In the case of RECOPOL, stimulating the well with a hydraulic fracture allowed the operators to achieve the target injection rate, while at Yubari, injecting nitrogen into the coal caused the permeability to recover. If large-scale sequestration and ECBM projects are to become a reality, these issues related to permeability and sorption strain need to be overcome.

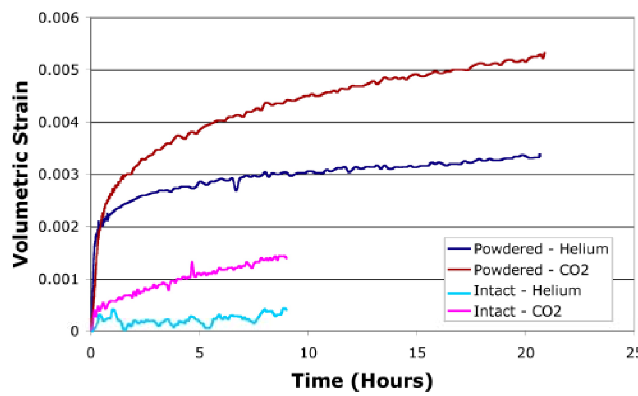

Figure 8: Volumetric creep strain plotted as a function of time for powdered and intact PRB coal samples, at a constant effective hydrostatic stress of 5 MPa. Notice that the intact, Helium saturated sample behaves elastically: there is no significant time-dependent strain. On the other hand, the intact, CO_2-saturated sample continues to deform as a function of time. The powdered samples show more complex behavior, but the CO_2-saturated sample still exhibits significantly more creep strain than the Helium-saturated sample.

The decrease in permeability following CO_2 saturation suggests that the coal matrix is swelling in response to adsorption. However, it is also possible that the adsorbed CO_2 is simply filling the pore space, and physically impeding flow. Distinguishing between these two effects is important for testing and building theoretical models relating adsorption and flow, but difficult in practice, because both mechanisms would cause a decrease in permeability.

9. CONCLUSIONS

Our research focus has been to conduct laboratory experiments on coal samples to improve and expand understanding of the effects of CO_2 adsorption on flow and mechanical properties. To date, we have made several key observations. Measurements of adsorption, swelling strain, and permeability change suggest that the effects of adsorption and stress on permeability are approximately the same order of magnitude. Because injection of CO_2 causes swelling, but decreases effective stress, these effects may cancel each other in situ. A related finding is that CO_2 causes the elastic stiffness of our coal samples to decrease, which should increase the sensitivity of permeability to stress. Combined with the observations of decreased stiffness, observations of creep strain suggest that coal becomes less brittle when exposed to CO_2. These observations require further study, but the implication for the near wellbore region in the field is that CO_2 makes coal more viscous and less elastic. Finally, P and S-wave velocity measurements show that CO_2 is detectable in coal, making 4-D seismic a possibility for monitoring, mitigation, and verification strategies.

10. ACKNOWLEDGEMENTS

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