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Matrix shrinkage and swelling characteristics of European coals

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Abstract

Matrix deformation experiments have been performed on a range of different rank coals subjected to carbon dioxide and methane sorption at representative in situ reservoir pressures under unconfined conditions. These experiments were complemented by a set of simultaneous gas permeability and strain measurements. The results were related to coal rank and the mechanical and elastic properties of each coal type tested. The measured CO_2 adsorption strains were consistently higher than those for methane, by a factor ranging between 1.3 and 4, depending on the coal type. The corresponding swelling coefficients were estimated in the range of 0.15 kg/m^3 to 1.0 kg/m^3 for methane and 0.25 kg/m^3 to 1.6 kg/m^3 for carbon dioxide. For the samples tested, matrix swelling due to CO_2 adsorption displayed a positive correlation with coal rank and resulted in a significant decrease in permeability.

Keywords: coalbed methane; matix swelling; permeability; coal rank.

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1. Introduction

The concept of injecting carbon dioxide into coal seams is considered to be a safe and effective method for permanently storing the CO_2 in coal with the added benefit of enhancing coalbed methane production (ECBM). Adsorption is the main storage mechanism in coal seams, which is distinctively different from that in conventional hydrocarbon reservoirs and aquifers. It is suggested that the CO_2 sorption capacity of coal seams is typically between 2 to 10 times higher than that for CH_4 depending on coal rank [1]. Thus, carbon dioxide enhanced coalbed methane recovery (CO_2-ECBM) is a technology that has the potential to store large volumes of anthropogenic CO_2 in deep unminable coal formations, while improving the efficiency and potential profitability of coalbed methane recovery. On the other hand, one of the technical obstacles faced in CO_2 storage/CO_2-ECBM recovery is that CO_2 induced matrix swelling can have a severe impact on well injectivity and storage capacity.

Coalbed methane reservoirs are described as naturally fractured, low-pressure gas reservoirs, usually saturated with water. Cleats are the natural fractures in coal, whose orientation is controlled by tectonic stresses at the time of their formation. Most of the permeability of coal seams is determined by the cleat network, and its magnitude can vary due to relative permeability effects; due to a change in the effective stress acting on the coal seam; or as a result of pore pressure effects on their matrix swelling/shrinkage behaviour. During primary methane production, two distinct phenomena are known to be associated with reservoir pressure depletion, which have opposing effects on coal permeability. The first is reservoir compaction due to pressure depletion, which causes an increase in the effective horizontal stress as the reservoir is confined laterally. The second is gas desorption from the coal matrix resulting in coal matrix shrinkage, and thus a reduction in the horizontal stress and an increase in cleat permeability. During enhanced methane recovery or CO_2 storage in coal, adsorption of CO_2 gas, which has a greater sorption capacity than methane, would cause matrix swelling and thus, in contrast to gas desorption, could potentially have a detrimental impact on cleat permeability of coal. Seidle and Huitt [2] have reported that swelling/shrinkage of coal matrix associated with CO_2 adsorption/desorption are typically two to five times larger than that seen for methane. Therefore, the

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expected reduction in field coal permeability caused by matrix swelling due to CO_2 pressurisation could be more significant than the increase in permeability already experienced due to matrix shrinkage during primary methane production [3].

Coal permeability is perhaps the most critical parameter for determining the economic viability of methane production from coal seams. Jones et al. [4] have reported that permeabilities of US coals range between 0.1 and 250 mD ($1\times10^{-16} – 2.5\times10^{-13}$ m^2), while European basins tend to possess much lower permeabilities in the range of 0.001 – 0.5 mD ($1\times10^{-18} – 5\times10^{-16}$ m^2). Durucan [5] found that coal permeability is highly dependent on stress and changes in permeability are also related to the coal's elastic roperties, as well as its tendency to develop microfractures/fractures when subjected to stress. Seidle et al [6] have reported that, during the early stages of production, permeability in the San Juan Basin has decreased by up to two orders of magnitude due to the increase in effective stress as methane is produced. However, it was also noted that absolute permeability could increase by up to 7 folds as the reservoir is depleted over a longer period of time.

The Langmuir [7] isotherm is most commonly used to describe adsorption behaviour in coalbed methane reservoirs, where the volume of gas adsorbed (V_a) at constant temperature is related to its pressure (P) by

$$V_a = \frac{V_L P}{P_L + P} \tag{1}$$

V_L is referred to as the monolayer adsorption capacity or Langmuir volume and represents the maximum quantity of gas that can be adsorbed. It is considered to vary positively with rank and inversely with temperature and moisture content. P_L is the Langmuir pressure corresponding to 0.5 V_L.

A number of researchers have investigated coal matrix deformation using pure methane and carbon dioxide. Most of them have calculated the shrinkage/swelling coefficients based on direct variation in volume with pressure. Tests carried out by Moffat and Weale [8] on low volatile bituminous and semi-anthracitic coals yielded a matrix swelling coefficient of 2.47×10^{-4} MPa^{-1} for methane. Reucroft and Patel [9] obtained a CO_2 swelling coefficient of 9.5×10^{-4} MPa^{-1} for samples taken from the Appalachian basin, while Gray [10] obtained a methane swelling coefficient of 1.25×10^{-4} MPa^{-1} for Northern Ishikari coal in Japan, and a CO_2 swelling coefficient of 1.82×10^{-3} MPa^{-1} using an Australian coal. In the majority of these early studies, CO_2 was found to cause coal swelling of the order of 2 to 5 times greater than methane. Harpalani and Schraufnagel [11] performed desorption tests on samples from the Piceance Basin for different gases under simulated reservoir conditions, and reported a methane shrinkage coefficient of 9.0×10^{-4} MPa^{-1}. Later, Harpalani and Chen [12] obtained a methane shrinkage coefficient of 2.3×10^{-4} MPa^{-1} for a coal from the San Juan Basin. In a more recent study, Mitra and Harpalani [13] reported methane and CO_2 matrix swelling coefficients of 10.7×10^{-4} MPa^{-1} and 38.7×10^{-4} MPa^{-1} respectively for the Herrin seam from the Illinois Basin. Chikatamarla et al. [14] carried out volumetric shrinkage and swelling experiments on Canadian coals varying in rank from sub-bituminous to medium volatile using N_2, CH_4, CO_2 and H_2S and reported that injection of H_2S causes swelling up to 5 times and CO_2 causes swelling more than 2.2 times the shrinkage caused by CH_4 desorption. Despite all these research efforts, the effect of coal type and rank on CO_2 sorption related matrix deformation is still not well quantified.

Seidle and Huitt [2] measured the matrix deformation of a sample of high volatile-C bituminous coal from the San Juan Basin undergoing adsorption and desorption of methane and CO_2. Their approach to analysing strain-pressure data differed from previous researchers in that the swelling coefficients were calculated by relating the degree of swelling to the volume of gas sorbed using a Langmuir type equation. By applying an analogy between strain-pressure data and sorption isotherm curves, the matrix shrinkage was found to correlate with sorbed gas content rather than directly with pressure. Average matrix swelling coefficients of 0.028 kg/m^3 and 0.025 kg/m^3 were reported for methane and CO_2 respectively.

2. Mechanical and elastic properties of the coals tested

Large coal blocks representative of coal ranks from High Volatile Bituminous to Anthracite were collected from opencast or underground coalmines in the United Kingdom, France and Germany. The coal samples used in this research included:

- the *Schwalbach* seam from the Ensdorf underground colliery in Saarland, Germany
- the *No.1* seam from the Warndt-Luisenthal underground colliery in Saarland, Germany
- the *Splint* seam from the Watson Head open cast site in Lanarkshire, Scotland
- the *Tupton* seam from the Carrington Farm open cast site in Derbyshire, UK
- the *Dora* seam from the Rumeaux underground colliery in Lorraine, France
- the *9ft* seam from the Selar open cast site in South Wales, UK
- the *7ft* seam from the Tower underground colliery in South Wales, UK

Samples taken from the coal blocks were cored or cut to sizes and used in different experiments. Before initiating the long-term the laboratory matrix deformation and permeability measurements the coals were characterised for rank, pore structure, cleat system, adsorption and mechanical/elastic properties as reported later in Table 1, together with their matrix deformation properties.

Simultaneous multistage triaxial compression and CO_2 stress-permeability tests were conducted on several 38 mm diameter core samples taken from the seven different coal types, under simulated reservoir stress and pore pressure conditions, using a four-column 2,000 kN capacity servo-controlled rock testing unit. The tests were performed in accordance with the ISRM recommended methods to define the mechanical and elastic properties of the coals used [15, 16]. Permeability reductions of up to two orders of magnitude were observed as the effective confining pressure was increased to 12 MPa.

The average Young's modulus calculated from these tests ranged from 1.10 to 3.90 GPa. These values are spread out across a much wider range than the corresponding average quoted for the San Juan Basin coals reported by Jones et al. [4], which was 3.0-3.7 GPa. Other the other hand, the Poisson's ratio varied over a smaller range between 0.26 and 0.42, which is comparable to the 0.23-0.40 range reported by the same authors. Based on the average Young's modulus values summarised in Table 1, Schwalbach coal appears to be the stiffest and offers the greatest resistance to being compressed by axial stress. Schwalbach also has the lowest Poisson's ratio, which indicates that there is a smaller degree of radial expansion relative to contraction in the longitudinal direction. Coals with a higher Young's modulus are less likely to be able to undergo physical deformation.

3. Matrix swelling and shrinkage experiments

The objective of these tests was to measure sorption induced volumetric changes in the coal matrix associated with variation in CO_2 and methane gas pressure. These were related to the mechanical and elastic properties of each coal type tested in order to understand the nature of matrix deformation and the extent to which it occurs. The term matrix deformation is used here to represent both shrinkage and swelling effects, unless specified otherwise.

A 10MPa high pressure membrane extractor cell manufactured by Soilmoisture Equipment Corp. was modified to connect to a strain monitoring bridge consisting of ten independent channels (Figure 1). The volumetric strains generated in the coal samples were measured using 10 mm one-way strain gauges attached to each sample. In view of the length of time (up to four months) required to complete a full cycle of adsorption/desorption tests for solid coal samples, the vessel was designed to take up to five samples simultaneously, with two strain gauges attached to each sample, aligned in the direction of the face and butt cleats. Cubic samples were cut from coal blocks to lengths ranging from 30 to 40 mm. It was ensured that the faces were smooth and in line with the bedding planes. Samples with visible cleats were avoided.

The vessel was first pressurised with helium, in stages up to 7 MPa to evaluate the baseline mechanical response of the matrix to a non-adsorptive gas. At each pore pressure, the strain readings were allowed to stabilise before moving on to the next pressure step. Once the maximum pressure had been reached, the cell was depressurised in stages. Strains were monitored as before by allowing the samples to attain equilibrium before progressing to the next pressure level. The process was then repeated using 99.7% purity methane gas, followed by pure carbon dioxide. In the case of methane, the sample cell was pressurised to 8 MPa, while for carbon dioxide a maximum pressure of only 5.5 MPa, which was the bottle pressure, was applied. Each time a new gas was introduced, the vessel had to be flushed with a non- adsorbing gas and evacuated in order to eliminate any remnants of the previous gas that may have become adsorbed onto the samples.

Results have indicated that the CO_2 adsorption strains were consistently higher than those for methane for all the samples tested. Strains were found to be greater by a factor ranging between 1.3 and 4 depending on the characteristics of the coal. As expected, helium data varied linearly with pressure and showed a slight reduction in volume due to grain compressibility effects. For a particular coal sample, the volumetric strain was calculated by adding the strain perpendicular to the bedding plane to twice that parallel to it, as established in standard rock mechanics literature. A typical set of matrix strain-pore pressure test results are presented in Figures 2 and 3 for different rank coals.

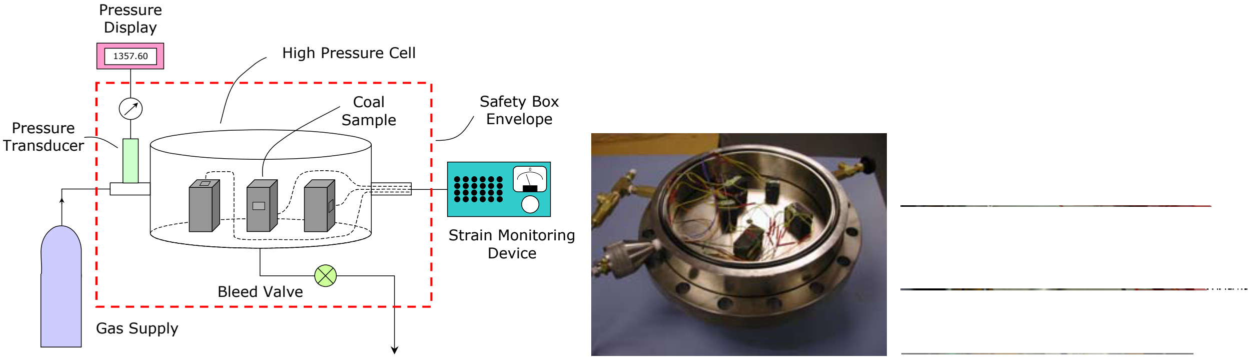


Figure 1. The experimental set-up used for matrix deformation tests and the 10 MPa high pressure membrane extractor cell used.

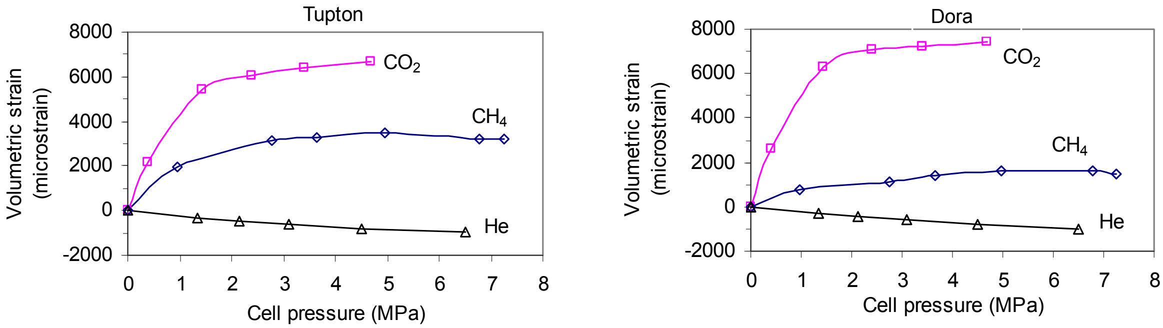
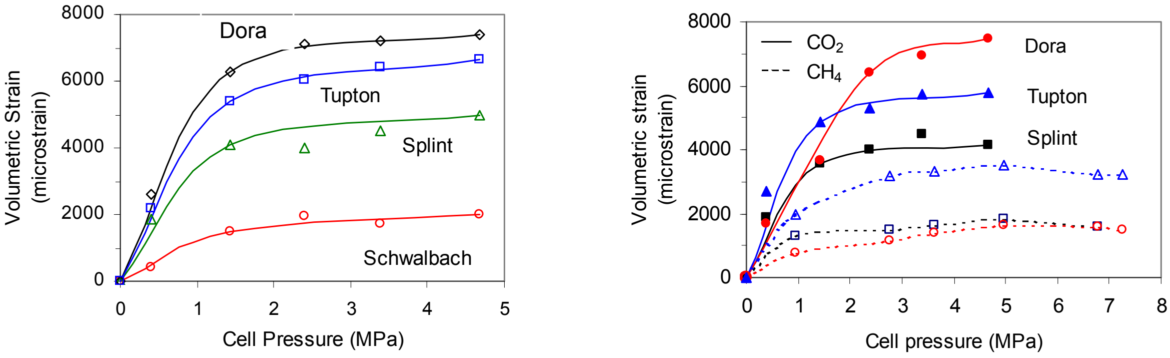


Figure 2. Measured volumetric matrix strains for He, CH_4 and CO_2 for the High Volatile Bituminous Tupton and Semi-anthracite Dora coal seams tested.



(a) matrix strain versus CO_2 sorption pressure

(b) matrix strain versus CO_2 and CH_4 sorption pressure

Figure 3. Typical CO_2 and CH_4 matrix strain curves for four different coals, demonstrating a strong correlation between matrix swelling and coal rank.

As shown in Figures 2 and 3, gas adsorption on coals generally follows a Langmuir type isotherm and does not exhibit significant hysteresis when pure gases are used. In most coals tested, the strain-pressure curves for CO_2 displayed this characteristic shape, as illustrated in Figure 3(a). Methane and CO_2 induced strains in different coals are compared in Figure 3(b). The curves correspond to selected samples that typify the behaviour that was observed. For methane, the strain-pressure curves displayed a somewhat curvilinear behaviour. However, the departure from the classical Langmuir shape was much more pronounced, with no substantial linear increase in strain during the early period, which is the case for CO_2.

The experimental work has shown that CO_2 adsorption strains were consistently higher (1.3 to 4 times depending on rank and matrix elastic properties) than those for methane for all the coal samples tested (Figures 2 and 3). These results were in agreement with the measurements reported earlier by Seidle and Huitt [2]. Assuming that matrix swelling is proportional to the volume of gas sorbed, and the sorbed gas is related to pressure by Langmuir's equation, the relationship between swelling and pressure can be written as [2]:

$$\varepsilon_m = \alpha V_L \frac{P}{P_L + P} \tag{2}$$

where ε_m is strain due to matrix swelling (set to zero at the atmospheric pressure), α is the matrix swelling coefficient (kg/m^3), P is pressure in MPa, P_L and V_L are the Langmuir parameters. In addition to sorption-induced swelling, the coal sample also experiences mechanical deformation under hydrostatic gas pressure loading. The associated strain (again set to zero at the atmospheric pressure) can be related to pressure by

$$\varepsilon_p = -c_p P \tag{3}$$

where c_p is the mechanical compliance coefficient of the sample (MPa^{-1}). In an experiment to measure matrix swelling of coal due to gas sorption, these two strains counteract. The strain recorded during the experiment is the net strain, and is given by

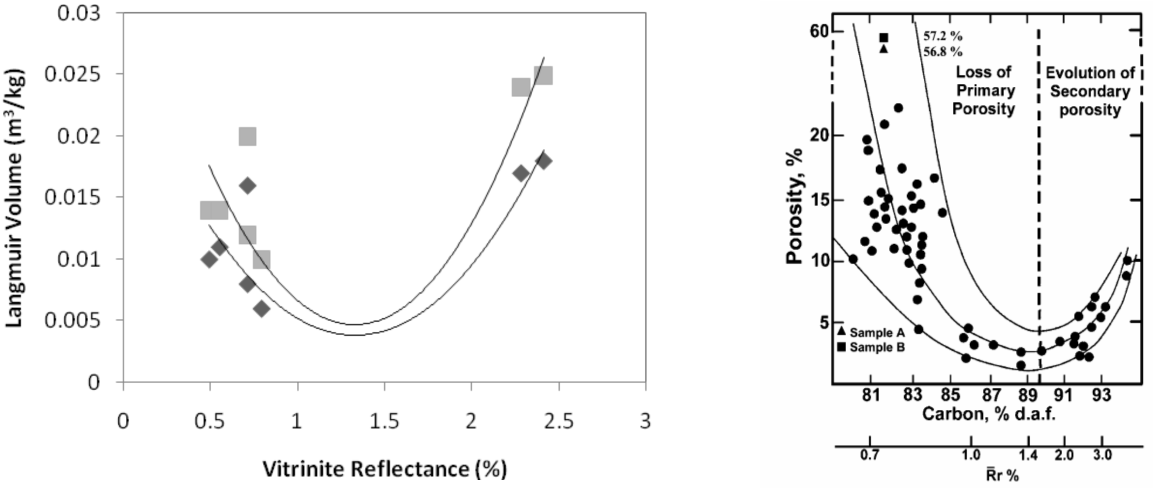
$$\varepsilon_{\exp} = \varepsilon_m - c_p P \qquad or \qquad \varepsilon_m = \varepsilon_{\exp} + c_p P = \alpha V_L \frac{P}{P_L + P} \tag{4}$$

The mechanical compliance coefficient for the coals tested was found from the helium strain data obtained during the experiments. The Langmuir parameters for the coals tested were determined from experimental adsorption isotherms produced at the Technical University of Delft (TUD) during a joint EU project ((ENK6-2000-00095) between Imperial College and TUD. The swelling data shown in Figure 3(a) were fitted to Equation (4) to yield α for each coal. It was observed that there is a correlation between CO_2 matrix swelling and coal rank, with the degree of swelling increasing with rank of coal, as illustrated in Figure 3(a) and Table 1 where the rank, elastic properties, Langmuir parameters and matrix deformation data determined for the seven coals tested in this study are presented.

The matrix swelling experiments have also shown that, for high rank coals such as Selar 9ft and Dora, the ratio between methane and CO_2 sorption induced strains was lower than that experienced for coals of lesser rank, such as Schwalbach. Whilst sorption capacity was found to generally increase with rank based on the strain-pressure curves determined during this research, the relationship was by no means a simple linear one as can be observed in Figure 4. The non linear trend between Langmuir volume, which is an indicator of the maximum sorption capacity, and Vitrinite Reflectance, appears to resemble the relationship between porosity and rank reported by a number of earlier researchers, including Rodrigues and Lemos de Sousa [17].

Table 1. Coal characterisation data obtained during the laboratory experiments and data analysis.

	Coal Seam						
	Schwalbach	W-L No.1	Splint	Tupton	Dora	Selar 9ft	Tower 7ft
Volatile Matter (d.a.f) %	43.6	41.6	40.2	35.3	16.5	10.2	9.1
Fixed Carbon (d.a.f.) %	56.4	58.4	59.8	64.7	83. 5	89.8	90.9
Vitrinite Reflectance (%)	0.79	0.71	0.55	0.49	0.71	2.41	2.28
Coal Rank	High Vol. Bituminous B	High Vol. Bituminous B	High Vol. Bituminous B	High Vol. Bituminous A	Semi-anthracite	Anthracite	Anthracite
Young’s Modulus, E (GPa)	3.20 – 3.90	2.19 – 2.69	1.80 – 2.30	1.10 – 1.62	2.41 – 2.84	1.75 – 2.58	1.82 – 2.26
Poisson’s Ratio, ν	0.26	0.42	0.34	0.36	0.38	0.40	0.32
Langmuir Volume, V_L (m^3/kg)	0.006 - 0.010	0.008 – 0.012	0.011 – 0.014	0.010 – 0.014	0.016 – 0.020	0.018 – 0.025	0.017 – 0.024
Langmuir Pressure, P_L (MPa)	3.75	2.44	2.00	1.05	2.50	0.77	1.84
Mechanical Compliance, c_p (x 10^{-6} MPa^{-1})	21.75	48.10	27.55	47.85	65.00	40.10	41.30
CO_2 Swelling Coefficient, α (kg/m^3)	0.31 – 0.55	0.25 – 0.80	0.50 – 0.62	0.55 – 0.77	0.53 – 0.66	0.50 – 1.62	0.78 – 1.52
CH_4 Swelling Coefficient, α (kg/m^3)	0.15	1.00	0.40	0.63	0.48	0.47	0.82



(a) (b)

Figure 4. The relationship between (a) Langmuir volume and rank determined in this research where the two curves represent the upper and lower ranges of the Langmuir volumes measured, and (b) porosity and rank as reported by Rodrigues and Lemos de Sousa [17].

The sorption capacity can be described as following a polynomial trend with increasing rank. A change in rank from medium volatile bituminous through to semi-anthracite gives rise to a temporary reduction in coal surface area and could be attributed to the micropore system becoming blocked by minerals or low boiling point hydrocarbon solids. As the rank increases further beyond this level, the micropore system opens up as a result of de-bituminisation and more surface adsorption sites become available. Thus the surface area for adsorption appears to vary with rank in a manner similar to pore size distribution. This is in line with separate studies by Levine [18], which suggests a second order polynomial trend between rank and sorption capacity.

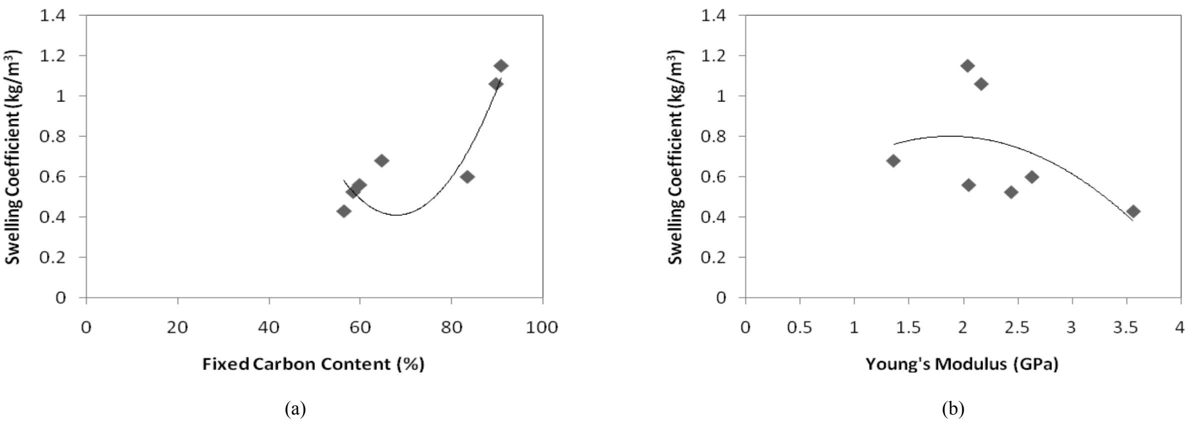
The matrix swelling coefficients obtained during this research ranged from 0.15 kg/m^3 to 1.00 kg/m^3 for methane and 0.25 kg/m^3 to 1.62 kg/m^3 for CO_2 respectively. The values were, on average, higher for CO_2 compared to methane. The range of the matrix swelling coefficients was also large, highlighting the heterogeneous nature of the coal pore structure. Compared to the swelling coefficients determined by Seidle and Huitt [2] for a high volatile-C bituminous coal from the San Juan basin (0.028 kg/m^3 and 0.025 kg/m^3 for methane and CO_2 respectively), the swelling coefficients obtained in this research are approximately an order of magnitude higher. However, it should be noted that Seidle and Huitt's tests were carried out at reservoir humidity and temperature, which may have had a bearing on the extent of matrix swelling.

As presented in Figure 5(a), the average CO_2 swelling coefficients show a polynomial correlation with carbon content, displaying an initial decline during the high to low volatile bituminous interval, followed by an indefinite rise in the swelling coefficient as the degree of matrix swelling increased with coal rank. This data appears to show similarities with the non-linear behaviour between sorption capacity and rank observed earlier. However, care should be taken in attributing correlations until more test results become available to provide data in the 60-80 % carbon content interval. The variation in average CO_2 swelling coefficients with Young's modulus is displayed in Figure 5(b). Apart from showing a weak polynomial trend with Young's modulus, the results are inconclusive and would require more tests to confirm such a relationship.

4. Simultaneous measurements of coal matrix swelling and permeability under CO_2 injection

Coalbed permeability models and the input parameters that are required for their use have been described in a number of recent publications by Seidle and Huitt [2], Palmer and Mansoori [3], and Shi and Durucan [19]. However, they do not explain the means by which these properties may be determined at reservoir pressure conditions. Harpalani and Chen [20] attempted to relate permeability change due to matrix deformation with volumetric strain, suggesting a linear dependence between the two parameters. However, the two variables were determined separately. More recent experimental studies by Zutshi and Harpalani [21] looked at the effect of CO_2 adsorption on coal swelling and the corresponding impact on permeability, but again the permeability was determined analytically using the geometric matchstick method first derived by Seidle et al [6].

The main objective of these experiments was to evaluate the effects of matrix shrinkage and/or swelling due to gas sorption on the absolute permeability of different coals, and the impact that carbon dioxide injection could have on coal absolute permeability. The tests focused on the flow behaviour in coal with variation in pore pressure as the coal underwent changes in permeability due to swelling of the matrix. These tests involved saturating coal samples with CO_2 or methane at various gas pressures and measuring both swelling and permeability at that pressure level. By performing the tests simultaneously, not only could the fact that matrix swelling takes place under dynamic conditions during CO_2 injection be verified, but also, the extent to which this deformation affects coal permeability may be quantified. At a later stage, this data is to be used to explore relationships linking cleat permeability, matrix strain and pore pressure.



(a) (b)

Figure 5. Variation in CO_2 matrix swelling coefficients with (a) carbon content, and (b) Young's modulus.

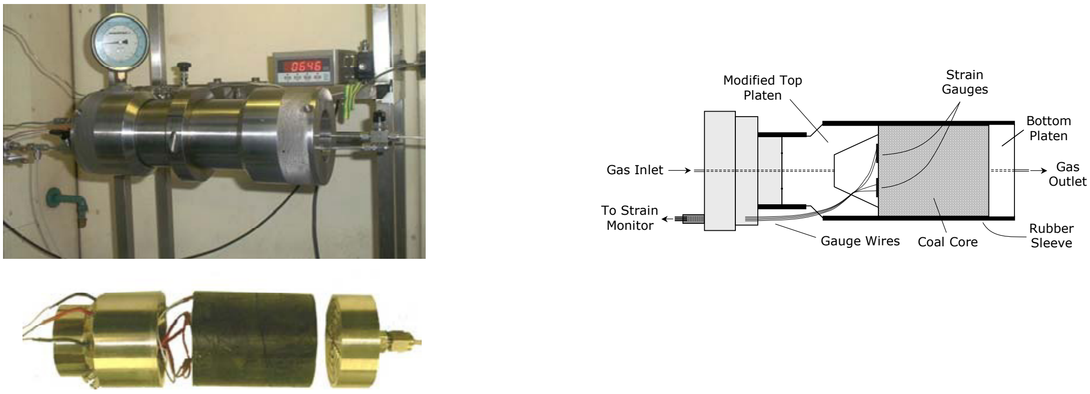
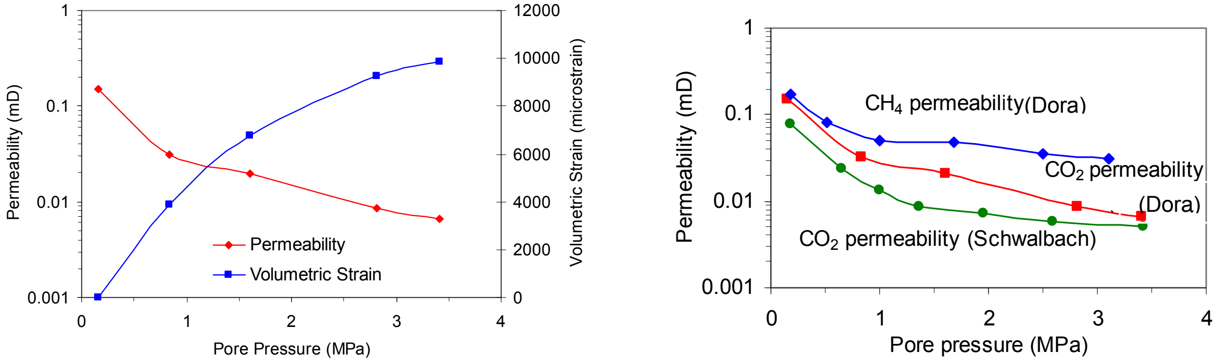


Figure 6. The simultaneous matrix swelling-permeability test set up showing the modified platen and associated parts of the Hassler cell core holder.



(a) Matrix strain versus CO_2 permeability

(b) CO_2 and CH_4 permeabilities versus sorption pressure

Figure 7. Simultaneous measurements of matrix swelling and permeability on coal samples at a constant confining pressure of 7 MPa.

In order to achieve a simultaneous measurement of coal matrix swelling and permeability under methane and CO_2 injection, a single core holder Hassler cell, capable of withstanding pore pressures of up to 15 MPa, was modified by the use of a newly designed and machined gas distribution platen. The new platen is placed at the upstream end of the cell and allows at least four strain leads to be fed through to gauges attached to one end of the coal sample tested. Figure 6 illustrates the modified platen and associated parts of the Hassler cell core holder and the detailed schematic/photographs of the experimental set up.

The freshly cut 50 mm diameter cores were initially placed in a desiccator to help remove any residual gas from the samples. These were then vacuum dried at 60 °C, in order to avoid oxidation. Normally, two single strain gauges were placed perpendicular to each other on a non-cleated area of the upstream coalface. Two-way rosette gauges were employed where the surface area available was judged to be limited. After loading the instrumented core sample in the cell, a confining pressure of 7 MPa was applied to the sample. The strain and permeability measurements were carried out in steps with increasing CO_2 or methane sorption pressure. Once the system had fully equilibrated at a given sorption pressure, gas flow was initiated and steady-state flow rate measured by regulating the upstream and downstream pressures.

Simultaneous measurements of matrix deformation and permeability were performed on a number of Lorraine and Schwalbach coals under a constant confining pressure of 7 MPa. When five cubic samples were being tested for matrix strain-pore pressure at constant temperature and pressure, only one permeability sample could be placed in the Hassler cell. Therefore, the tests were not repeated on other coal types available in the sample set. Schwalbach and Lorraine coals were chosen because they are located at opposing ends of the coal rank spectrum. Both were also extracted from underground mines, and were therefore more representative of in-seam behaviour. Furthermore, their structural condition was generally more favourable and consisted of a good balance of cleats and matrix, unlike Selar 9ft, Tower 7ft and Splint, which were all heavily fractured. Examples of simultaneous matrix swelling-permeability test results are presented in Figure 7.

Simultaneous swelling and permeability tests have shown that matrix swelling has a significant impact on coal permeability, as is illustrated in Figure 7a. As the CO_2 sorption pressure was increased from near zero to 3.5 MPa, under a constant confining pressure of 7 MPa, a reduction in permeability of about one order of magnitude was observed. One would normally expect an increase in permeability due to reduction in the effective stress as the pore pressure rises. However, the fact that permeability is reduced indicates that sorption induced matrix swelling was the more dominant effect. Figure 7b compares CO_2 permeability variation with sorption pressure for the Schwalbach and Dora coals. Both coals show steady decline in permeability with increasing sorption pressure. It is noticeable that the Schwalbach coal permeability follows a gentler trend than the Dora coal from 1 MPa onwards. This may be attributed to the fact that it has a relatively larger matrix Young's Modulus (Table 1) and therefore has undergone less swelling at comparable pore pressures. For comparison, the measured CH_4 permeability for the Dora coal is also plotted in Figure 7b. This further underlines the impact of CO_2 matrix swelling on coal permeability. The experiments have shown that, when compared to the high volatile bituminous coals, higher rank coals in the semi-anthracite and anthracite range swelled more when subjected to the same pore pressures.

5. Conclusions

This paper presented the matrix deformation experiments that were performed on a range of coal types subjected to carbon dioxide and methane sorption in order to better understand the CO_2 injectivity and storage characteristics of coal. A high-pressure membrane extractor cell was adapted in order to perform the tests, and sorption induced coal matrix swelling was successfully demonstrated. Swelling coefficients were obtained in the range of 0.15 kg/m^3 to 1.00 kg/m^3 for methane and 0.25 kg/m^3 to 1.62 kg/m^3 for carbon dioxide. A positive correlation between CO_2 matrix swelling and coal rank was observed, with the degree of swelling increasing with carbon content. This relationship was generally in keeping with the pore size distribution of coals. However, the trend for methane swelling was less clear. Results have also shown that matrix swelling caused by CO_2 injection has a severe impact on coal permeability, confirming the outcome of field pilots reported in the literature.

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