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International Journal of Coal Geology 66 (2006) 204 – 216
International Journal of COAL GEOLOGY
www.elsevier.com/locate/ijcoalgeo

The effect of CO_2 on the geomechanical and permeability behaviour of brown coal: Implications for coal seam CO_2 sequestration

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Received 16 May 2005; received in revised form 30 August 2005; accepted 4 September 2005
Available online 19 October 2005

Abstract

Theory from fracture mechanics and thermodynamics coupled with the results of experimental studies provides evidence to suggest that the adsorption of carbon dioxide on coal causes a decrease in the coal strength. Coal weakening by the introduction of CO_2 to a coal seam may induce fracturing, causing a permeability increase under in situ conditions. Such effects present significant implications for proposals regarding the storage of CO_2 in coal seams.

A uniaxial and triaxial laboratory study was carried out to explore the effects of the adsorption of CO_2 on the compressive strength and permeability of southeast Australian brown coal. Comparison of the stress–strain response of air-saturated and CO_2-saturated specimens revealed a compressive strength decrease in the order of 13% and an elastic modulus decrease of about 26% for the uniaxial testing, but no significant strength or elastic modulus decrease for the triaxial testing. The absence of an adsorptive effect on the mechanical behaviour of the triaxial specimens may have been due to an insufficient saturation period under simulated ground conditions, or due to mechanical variability in the brown coal test specimens, however, further testing is required to reveal the reason for the apparent negligible strength reduction with CO_2 adsorption at the higher confinement. Carbon dioxide outflow measurements during the stress–strain process demonstrated an initial permeability decrease with pore closure, followed by a significant increase in specimen permeability with fracturing.

Issues that require consideration in the application of these results to coal seam CO_2 sequestration include: whether the expected regional and localised in situ stresses are sufficient to initiate fracturing with adsorptive weakening; how coal properties (e.g. rank, moisture content) are likely to affect the geomechanical influence of CO_2 adsorption, and the expected magnitude of the proposed fracture related permeability increase.

Keywords: Coal; CO_2 sequestration; Adsorptive weakening; Geomechanics; Permeability

1. Introduction

With global targets for the decrease of greenhouse gas emissions, attention has turned to the capture and storage of carbon dioxide in geological media. Proposals for CO_2 storage have included plans to sequester CO_2 in deep, unminable coal seams, with the possibility for enhanced coal bed methane recovery. Coal seam CO_2 sequestration involves adsorption of CO_2 to the coal surface in large quantities, a process that, from thermodynamics and fracture mechanics theory, field experience and the results of experimental studies, is thought to lower the strength of the coal. Under in situ stresses, a coal strength decrease with the sequestration

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0166-5162/$ - see front matter
doi:10.1016/j.coal.2005.09.002

of CO_2 may cause fracturing of the coal, forming flow networks that could allow migration of sequestered CO_2 back out of the sequestered zone and into adjacent and overlying units, invalidating the retention process and possibly posing safety hazards. Such concerns cast doubt over the geomechanical and CO_2 migration stability of coal seam CO_2 sequestration.

1.1. CO_2 storage mechanisms in coal

Carbon dioxide can exist in coal in three different states, as a free gas within pore spaces, dissolved in pore space liquids or as a gas adsorbate bonded to the coal surface. Thus, the retention potential of a given coal is dependent on a number of factors, including but not exclusive to its chemistry, its surface area to volume ratio and its moisture content. The moisture content of a coal can have strong controls on the geomechanical influence of the introduction of CO_2 as the above-mentioned hypothesised weakening is related specifically to the adsorptive retention of CO_2 and if a greater volume of liquid is available to dissolve CO_2 less will require storage by such a process.

1.2. Coal weakening by adsorption of CO_2

1.2.1. Fracture mechanic and thermodynamic theory

Griffith's Failure Criterion (Griffith, 1921) of Eq. (1) provides an expression for the strength of a material, defining the tensile stress at an existing crack tip, σ, required to form a new crack surface.

$$\sigma = \sqrt{\frac{2\gamma E}{\pi a}} \quad (1)$$

where γ is the surface energy per unit crack length, E is Young's modulus of the material and a is the crack half length.

Gibbs Adsorption Equation (Gibbs, 1921) relates a change in surface energy to the amount of adsorption of a given phase:

$$d\gamma = -\sum_i (\Gamma_i d\mu_i) \quad (2)$$

where $d\gamma$ is the change in the surface energy associated with adsorption and Γ_i and $d\mu_i$ are the surface concentration and change in the chemical potential of the ith adsorbate component, respectively.

According to Gibb's Adsorption Eq. (2), surface energy can diminish due to an uncompensated increase in concentration of an existing adsorbate, any change in the adsorption environment that increases the chemical potential of the adsorbate, or due to the exchange of an existing adsorbate for a more reactive one with greater chemical potential. Griffith's equation for the tensile strength of a cracked solid (1) states that a decrease in surface energy will be associated with a decrease in the tensile stress at the crack tip required to form a new crack surface. Thus, it follows that modifications to the adsorbate–adsorbent system that cause a decrease in the surface energy will also cause a weakening of the material.

Consequently, by the postulates of Griffith (1921) and Gibbs (1921), it is expected that a strength reduction will be observed upon exchange of an existing adsorbate for one with which the associated chemical potential of bonds between the adsorbate and the adsorbent are greater. Strength reduction achieved by adsorption related lowering of the crack initiation stress threshold is expressed (3), found by substituting Gibb's Adsorption Eq. (2) into Griffith's equation for the tensile strength of a cracked solid (1).

$$d\sigma = \sqrt{\frac{2E\sum_i (\Gamma_i d\mu_i)}{\pi a}}. \quad (3)$$

Surface energy lowering, according to Gibbs' Adsorption Equation, and an associated decrease in the tensile strength of existing cracks in a solid body, as described by Griffith's Failure Criterion, have been used to explain: the long-term strength reduction of glass in air in comparison to glass in a vacuum (Orowan, 1944); the strength reduction caused by water vapour on compacted silica (Dollimore and Heal, 1961); weakening due to water vapour on compacted discs of powdered coal (Dollimore et al., 1965), and coal strength reduction by CO_2 saturation (Ates and Barron, 1988).

1.2.2. Previous studies

It has been long recognised by mining engineers that the mechanical character of coal is dependent on the amount of coal seam gas entrained (Beamish and Crosdale, 1998; Ettinger and Lamba, 1957). Such dependence is well demonstrated by the hardening of coal upon the release of gases during mining (Ettinger and Lamba, 1957). The susceptibility of coal to the spontaneous failure phenomenon in underground mining known as 'outburst' is dependent on the composition of the gases within the mined coal seam; in the presence of high concentrations of CO_2, coal becomes vulnerable to outburst (Beamish and Crosdale, 1998; Lama and Bodziony, 1996, 1998). Previous studies have employed a number of innovative experimental methods to explore the effect of CO_2 on coal strength, the majority carried out in an attempt to understand the effects of CO_2 adsorption on coal outburst behaviour.

Ettinger and Lamba (1957) tested crushed coal samples consisting of 6.5 to 7 mm particles by means of mechanical pounding using a standard drop weight and drop height. Having sieved the crushed material, they used the mass of 'dust residue' (material passing through a 0.5-mm sieve) as an indication of the relative hardness of the original sample. This qualitative approach to studying material hardness assumes that a certain material, crushed using a standard process, will contain a higher proportion of fines than the remains of a stronger (harder) material crushed employing the same standard process. Tests were carried out in air and CO_2 environments at a pressure of 4.0 MPa. The natural gases were evacuated from the samples to be tested in the CO_2 medium by means of a vacuum applied for a period of 3 h. A CO_2 environment was established and the samples were left for 13 h prior to testing to allow gas sorption. These experiments suggested that the effect of CO_2 on coal strength is dependent on the degree of fracturing and that 'disturbed' coals show a typical strength index reduction by a factor of about 0.75 with the sorption of CO_2 in comparison with samples tested in air. Fig. 1 shows the increase in dust quantity from crushing in the presence of CO_2 in comparison with air, interpreted as being due to a decrease in coal strength with the adsorption of CO_2.

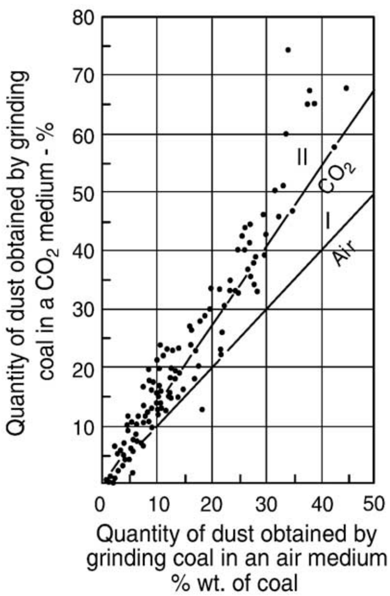

Fig. 1. Quantity of dust obtained by crushing in the presence of CO_2 (II) with respect to crushing in air (I) (modified from Ettinger and Lamba, 1957).

Czapliński and Holda (1982) studied the resistance of low-rank 4-mm coal cubes to crushing under two separate conditions containing different gas environments and pressures. They used a ram-loading device and dynamometer to determine the loads at which coal specimens failed in an air atmosphere at 0.1 MPa and in a CO_2 atmosphere at 2.0 MPa. In the case of the CO_2 sorbed tests, samples were kept in the CO_2 medium for a period of 48 h prior to crushing. Results suggest that CO_2 saturation at the higher pressure reduced the crushing resistance of the samples by more than 44%. However, it must be acknowledged that CO_2 tests by Czapliński and Holda (1982) were carried out at greater pressures than their air tests. This is likely to have contributed to the lower crushing resistance of the CO_2-saturated specimens in accordance with an effective stress decrease in the coal specimens.

The tests of Vinokurova et al. (1988) involved the pulverisation of anthracite samples saturated with He, CH_4, and CO_2 gas at 3.5 MPa and air at atmospheric pressure, utilising a vibration mill operating at a frequency of 3000 cycles/min, with an amplitude of 2 mm for 60 s in the crushing process. Like Ettinger and Lamba (1957), they used the particle size distribution after crushing as a hardness index that denotes the strength of the sample. Samples were exposed to the respective gas involved in the experiment for 3.5 days at a pressure of 3.5 MPa before crushing. The results from the testing program suggested that CO_2 saturation had a significant weakening effect on the coal, producing a crushed fraction of anthracite up to one order of magnitude greater than that obtained for the air 'control' sample. The saturation of the sample with CO_2 caused a greater decrease in strength than saturation with CH_4, while both phases caused a greater weakening than with He. This was interpreted as being due to the 'surface-active', adsorbing nature of both CH_4 and CO_2 in comparison with the inert He.

The strength of intact coal samples was tested in a vacuum and at pressures of 0.345, 1.035 and 3.45 MPa in both CO_2 and He environments by Ates and Barron (1988) using Brazilian tensile strength tests. Prior to testing each sample, they applied a vacuum for half an hour to evacuate existing gases in the sample. In the case of the He- and CO_2-saturated samples, pressure was applied for a period of 24 h prior to testing to allow sorption of the gas phase. Initial test results suggested that the sorption of CO_2 caused a 0.13 MPa (approximately 14%) reduction in coal strength at a pressure of 3.45 MPa, whereas the sorption of He was associated with no strength change at the same pressure. However, Ates and Barron (1988) suspected that the strength decrease in the CO_2 samples was caused by damage due to sudden pressurisation; the relatively small molecular size of He causing negligible change while pressurisation with the larger CO_2 molecules resulted in significant damage. To validate their results, they carried out a second set of tests where samples were pressurised incrementally, with adequate time to stabilise between subsequent injections. Results using the modified approach showed no significant difference in coal strength with the sorption of different gas phases. From this, they concluded that CO_2 adsorption causes no reduction in the strength of coal.

To study the effects of gas sorption on coal strength, Aziz and Ming-Li (1999) precision drilled a number of coal samples saturated with different gases at different pressures within pressure chambers. They used a standard 6.5 mm masonry drill bit thrust into the coal samples, applying a constant force. Their investigation of the effects of sorbed gas on the strength of coal was based on the assumption that both the resistance that a coal sample offers to drilling and the particle size distribution of the drill cuttings produced are related to the strength of the coal, with faster drill speeds and larger cuttings signifying weaker material. Drill speeds and rates were observed and cuttings were sieved to determine particle size distributions. Tests were carried out in air at atmospheric pressure, CO_2 at 1.5 MPa, a 50% CH_4 and 50% CO_2 mixture at 1.5 MPa, CH_4 at 1.5 MPa, and CH_4 at 3.0 MPa. In addition to showing the greatest drilling rate of all samples (Fig. 2), the drill cuttings of the CO_2-saturated specimen contained a greater proportion of coarse particles than samples saturated with other sorbed phases. Based on their assumptions, the sorption of CO_2 produces a greater decrease in coal strength than does the sorption of the other gas phases tested.

With the exception of Ates and Barron (1988), these results provide persuasive evidence to suggest that an increase in the concentration of CO_2 in coal seam gases will cause a decrease in the strength of the coal seam and thus produce a marked change in its geomechanical behaviour. It must be emphasised that due to the fact they were carried out within the framework of coal outburst, the experimental studies summarised above did not consider the effect of in situ stresses encountered at depth within an intact (as opposed to a mined) coal seam. Such a consideration is integral to the investigation of the geomechanics of coal bed CO_2 sequestration.

1.3. Coal-CO_2 permeability with fracture

In light of the perceived adsorptive weakening of coal, an understanding of the eventual effect of the introduction of CO_2 on the sequestration potential of a coal seam requires an understanding of the influence of fracturing on the CO_2 permeability of coal under in situ conditions and the associated potential for CO_2 flow out of the sequestered zone.

For a fractured porous mass, flow occurs both through the intact matrix and through the fracture system. Hence, the total permeability of the porous mass (k_t) can be found by the addition of the matrix permeability (k_m) and the fracture permeability (k_f):

$$k_t = k_m + k_f \tag{4}$$

Ignoring the effects of gravity and the velocity head of the flow, fluid flow for a porous mass is given by

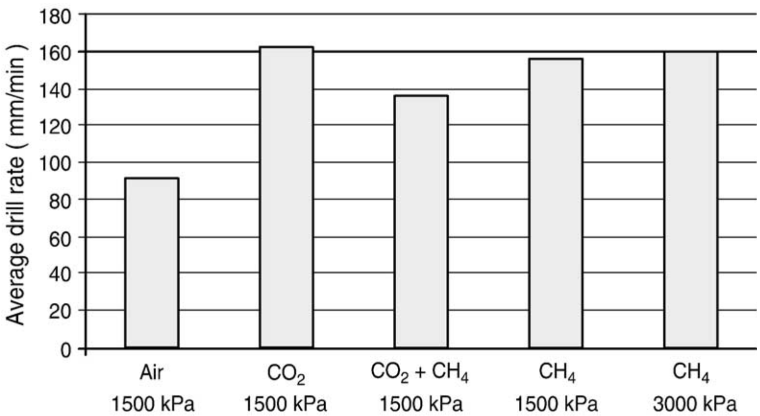

Fig. 2. Average drill rate for various sorbed phases (from Aziz and Ming-Li, 1999).

Darcy's law (5), employing the total permeability term.

$$q = \frac{k_t}{\mu}\frac{\partial P}{\partial l} \quad (5)$$

where μ is the dynamic viscosity of the flowing fluid and $\frac{\partial P}{\partial l}$ is the pressure gradient in the flow direction.

In most systems where flow occurs through a fractured porous medium, fracture flow will account for a proportionately greater amount of the total flow than matrix flow. This is well demonstrated by the greater productivity achieved from fractured oil and natural gas reservoirs due to the relative ease of extraction associated with the greater flow rates through fractured media when compared to intact media.

Experimental investigations performed by Wang and Park (2002) concerning the flow of water through sedimentary rock during the triaxial stress–strain process demonstrated a decrease in axial permeability with increasing axial stress to the point of failure. Following failure, a sudden, steady increase in axial permeability to a maximum value was noted. The researchers interpreted the initial permeability decrease as due to compression and closure of pore spaces during a progressive increase in axial load and the sudden, post-failure permeability increase as due to the formation of new flow paths by fracturing, with peak flows corresponding with fracture dilation during movement along the failure plane. The results of the laboratory work carried out by Wang and Park (2002) are summarised in the plots of Fig. 3.

Somerton et al. (1975) drew similar conclusions to those of Wang and Park (2002) in their investigations into the effect of stress on the permeability of bituminous coal to gas (methane and nitrogen). They found that the permeability of coal to gas was strongly stress dependent, with specimen permeabilities decreasing with increasing applied stress, to the point of failure, where an increase in permeability was observed, also interpreted as being due to the formation of new flow paths by fracturing.

2. Laboratory testing program

2.1. Coal origin and properties

The brown coal used in the testing program was obtained from Yallourn Energy's open pit mining

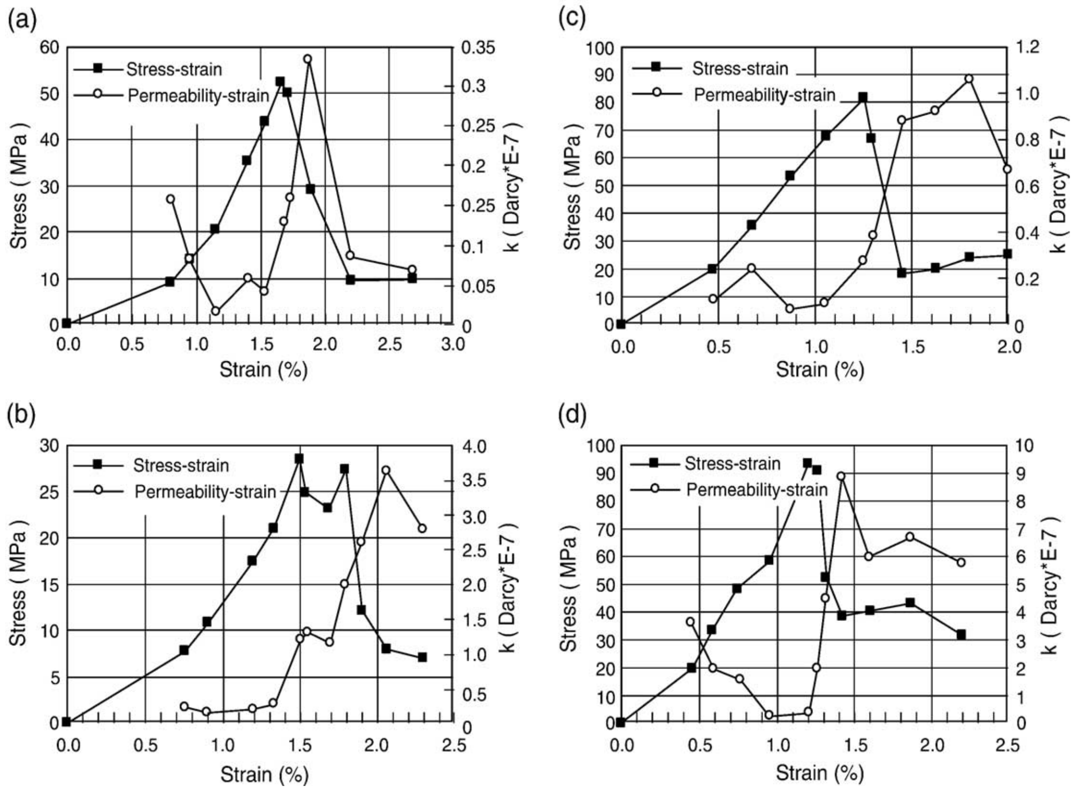

Fig. 3. Results of tests for permeability during the stress–strain process of rocks in triaxial compression: (a) mudstone, (b) sandy shale, (c) fine grained sandstone, (d) medium grained sandstone (from Wang and Park, 2002).

Table 1
Typical Yallourn Seam brown coal properties, after Brockway and Higgins (1991) and average values calculated from testing

Property	Typical value	Calculated value
Rank	Lignite	×
Specific gravity	1.127	1.117
Moisture content (% wb)	66.5	62.0
Ash yield (% db)	1.7	×
Volatile matter content (% db)	50.3	×
Fixed carbon (% db)	48.0	×
Sulphur content (% db)	0.28	×
Gross dry specific energy (MJ/kg)	26.1	×
Net wet specific energy (MJ/kg)	6.9	×

db = dry basis, wb = wet basis, × = not calculated.

operations in the Latrobe Valley of Victoria, Australia. The coals of the Latrobe Valley provide most of Victoria's power, with current production averaging over 40 million tonnes per year from three mines (Holdgate, 2003). Mining for Yallourn Energy is carried out in the Yallourn Seam, which is within the Yallourn Formation, the youngest of three major Tertiary age, brown coal-bearing sequences in the Latrobe Valley. Table 1 shows typical values of Yallourn Seam brown coal properties as detailed in Brockway and Higgins (1991). Moisture content and density calculation of the specimens tested in this study revealed an average moisture content of 62.0% (calculated on a wet basis) and a specific gravity of 1.117.

2.2. Specimen preparation

Specimens for the testing component of the study were cored (core diameter = 54 mm) from large brown coal samples, with those from a common sample block labeled with the same letter prefix (A, B, C or D). All uniaxial specimens were cored from one sample block (A) whereas triaxial specimens were taken from three separate sample blocks (B, C and D). Greater potential for variation in the character of triaxial specimens due to mixed sources is later discussed. Cored specimens were cut at each end using a diamond saw, to produce cylindrical specimens of length between 2.0 and 2.3 times the core diameter. Prepared specimens were wrapped in several layers of plastic and then stored in a sealed bag until testing to avoid comparison of the results of tests carried out on specimens with moisture contents that differ significantly. Furthermore, to avoid changes in coal character due to aging of coal specimens, all comparable tests were carried out in succession within the space of 2 to 3 weeks. To study the effects of CO_2 on the geomechanical behaviour of coal, the test program compared the axial stress–strain behaviour of CO_2-saturated specimens to that of specimens containing air. To produce the CO_2-saturated specimens, the test specimens were exposed to pure, pressurised CO_2 (at 1.5 MPa) for a sustained period prior to testing, while non-CO_2 specimens were exposed to pressurised air (at 1.5 MPa) prior to testing. In each case, the pressure was maintained for 72 h, after which it was relieved and the specimen was removed for testing. Studies of the effect of CO_2 adsorption on coal strength carried out by Ettinger and Lamba (1957) and Czapliński and Holda (1982) successfully used 13- and 48-h adsorption periods, respectively, to obtain meaningful results and thus, it was expected that a 72-h saturation period is sufficient for the purpose of investigating the weakening effect of CO_2 on coal.

2.3. Laboratory methodology

The testing program explored the effect of CO_2 adsorption on the stress–strain behaviour of coal by means of uniaxial testing of four CO_2-saturated and three air-saturated specimens and high-pressure triaxial testing of four CO_2-saturated and four air-saturated specimens. Tests were carried out on a triaxial rig specifically modified to recreate the conditions of coal seam CO_2 sequestration. The uniaxial testing provided a preliminary indication of the effects of CO_2 on coal strength while the high-pressure triaxial testing component was designed to allow an understanding of the influence of CO_2 adsorption on coal under in situ conditions, providing insight into the effects that CO_2 injection may have on the geomechanical behaviour and, in the case of one test (specimen C3), fracture permeability of brown coal in coal seam CO_2 sequestration.

High-pressure triaxial tests employed confining pressures of 10 MPa and internal specimen gas pressures of 2.0 MPa. Such pressures conservatively represent a geologically under-pressured situation. Future testings will be carried out at pressures representing equivalent depths for CO_2 coal seam sequestration. Both the uniaxial and triaxial investigations used a constant axial strain rate.

2.3.1. A new two-phase triaxial device

Laboratory modeling of CO_2 coal seam sequestration requires modifications to a conventional high-pressure triaxial testing apparatus, to allow the application of internal gas and fluid pressures to the specimen and to allow accurate quantification of liquid and gas outflows with time during the stress–strain process. The changes made to a high-pressure triaxial device for the purposes of this study were, specifically, the creation of a gas

Fig. 4. Customised triaxial device.

inflow system that applies an internal gas pressure to the triaxial specimen and the adaptation of the two-phase outflow system, allowing measurement of expelled gas and liquid flows. The customised two-phase, high-pressure triaxial testing apparatus at the Monash University Geomechanics Laboratories is shown in Fig. 4 and a schematic of the setup is shown in Fig. 5.

3. Results and discussion

3.1. Uniaxial testing

Uniaxial specimens were noted to fail through the coal matrix or along significant preexisting inhomogeneities, commonly in the form of large wood

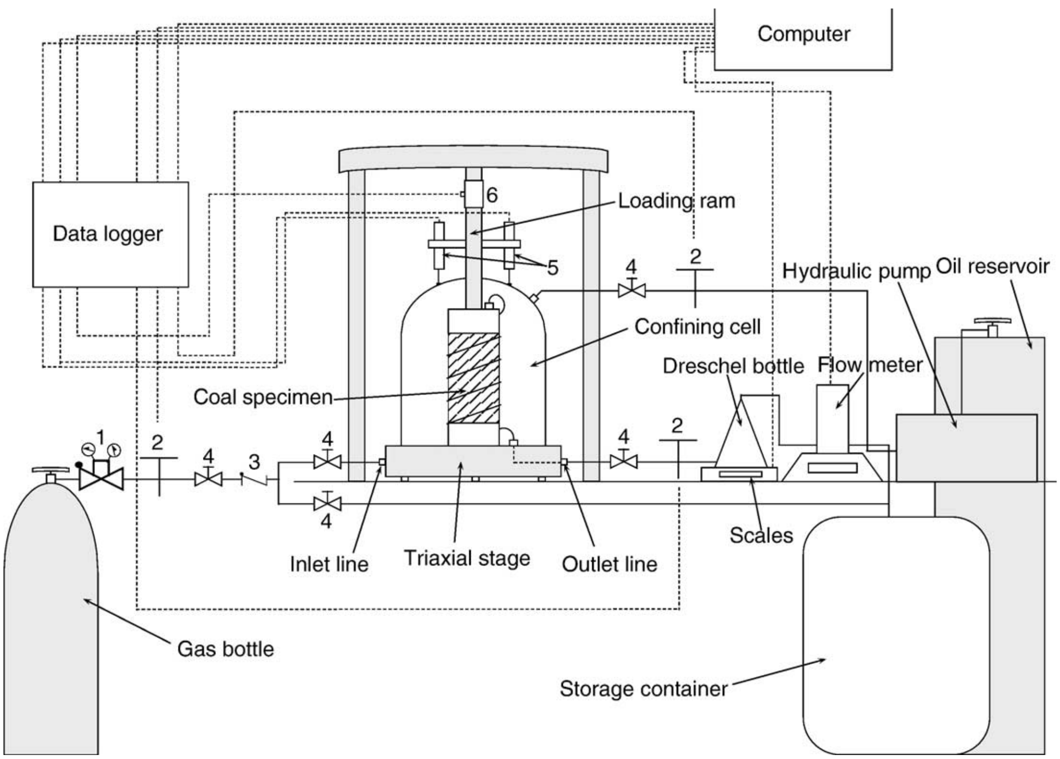

Fig. 5. Schematic diagram of the modified, two-phase high pressure triaxial apparatus. (1) Pressure regulator, (2) pressure transducer, (3) one-way valve, (4) quarter turn valve, (5) displacement transducer, (6) load transducer.

Fig. 6. Typical failed uniaxial specimens.

pieces. Specimens that failed along 'woody' irregularities were not considered in calculations for the average unconfined compressive strength (UCS) of the brown coal and the results of these tests are not here presented. Fig. 6 shows typical failed specimens from the uniaxial testing.

Average unconfined compressive strengths of 0.844 ±0.108 MPa and 0.966±0.128 MPa were obtained for CO_2-saturated and air-saturated specimens at the 95% confidence level, respectively. Excluding inconsistent tests, as in the case of average UCS results, an average elastic modulus of 41.6±2.2 MPa and 56.2±8.3 MPa was found for the CO_2-saturated and air-saturated specimens at the 95% level of confidence, respectively. Compressive strength is plotted against elastic modulus for each of the uniaxial specimens tested (Fig. 7). The discrete grouping of data for the CO_2- and air-saturated specimens, respectively, demonstrates the dependence of CO_2 content on the geomechanical behaviour of the uniaxial specimens.

Fig. 8 compares the uniaxial loading response of CO_2-saturated and air-saturated specimens, considering only specimens that failed through the matrix. Table 2 gives a summary of results for the uniaxial testing.

From the results of the uniaxial testing, there is significant evidence to suggest that the introduction of CO_2 has an effect on the geomechanical behaviour of brown coal, decreasing its UCS and its elastic modulus. Though further experimental work is required to confirm such results, on the basis of this study, an unconfined compressive strength reduction in the neighbourhood of 13% and an elastic modulus reduction of approximately 26% appear to apply to the brown coal with the adsorption of CO_2. Typical data obtained from the uniaxial testing is presented and treated in Viete et al. (2005).

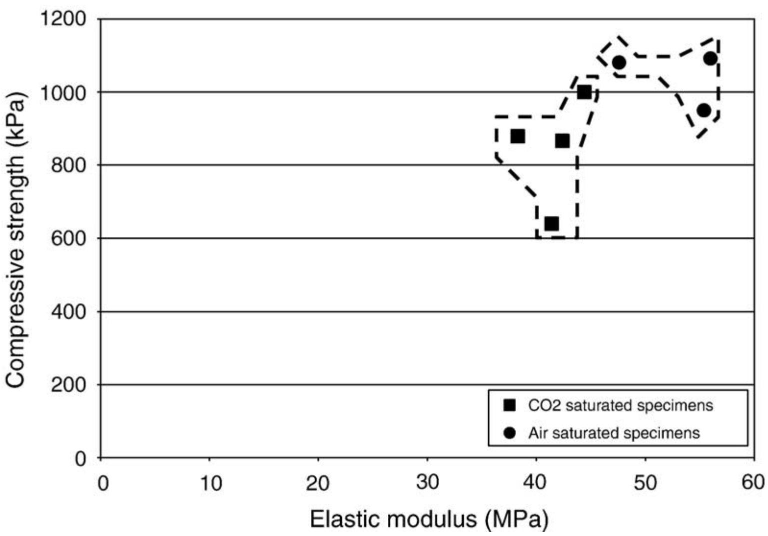

Fig. 7. Compressive strength vs. elastic modulus plots for CO_2- and air-saturated uniaxial specimens.

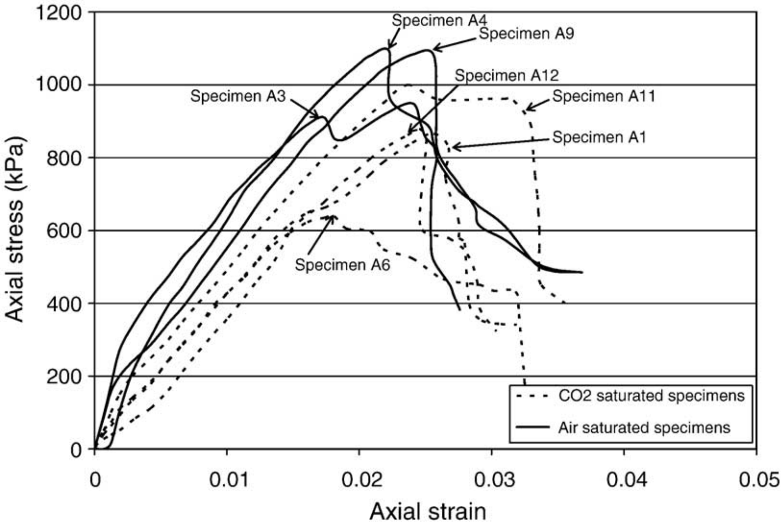

Fig. 8. Comparison of axial stress–strain behaviour for unconfined CO_2- and air-saturated specimens (from Viete et al., 2005).

3.2. Triaxial testing

In total, eight triaxial tests were carried out in the testing program. Of the eight, four tests were carried out on CO_2-saturated specimens and a further four on air-saturated specimens. Fig. 9 shows typical failed specimens from the triaxial testing.

An average compressive strength of 12.904±0.403 MPa was obtained for CO_2-saturated specimens tested at 10 MPa confinement with an internal gas pressure of 2.0 MPa at the 95% level of confidence, while air-saturated specimens at the same confinement and internal pressure showed an average compressive strength of 12.959±0.439 MPa, at the 95% confidence level. For the same tests, an average elastic modulus of 73.2±11.9 MPa and 60.2±12.1 MPa was found for the CO_2-saturated and air-saturated specimens at the 95% level of confidence, respectively. Compressive strength is plotted against elastic modulus for each of the triaxial specimens tested (Fig. 10). The apparent lack of a CO_2-related influence on the geomechanical behaviour of brown coal in the triaxial testing program is shown by the relatively 'random' distribution of

Table 2
Summary of uniaxial test results

Specimen	Saturation gas	Unconfined compressive strength (kPa)	Elastic modulus (MPa)	Moisture content (% wb)
A3	Air	950	55.4	62.3
A4	Air	1092	56.0	61.9
A9	Air	1081	47.6	62.2
A1	CO_2	866	42.4	61.7
A6	CO_2	639	41.4	62.4
A11	CO_2	1000	44.4	61.6
A12	CO_2	879	38.3	61.4

Fig. 9. Typical failed triaxial specimens.

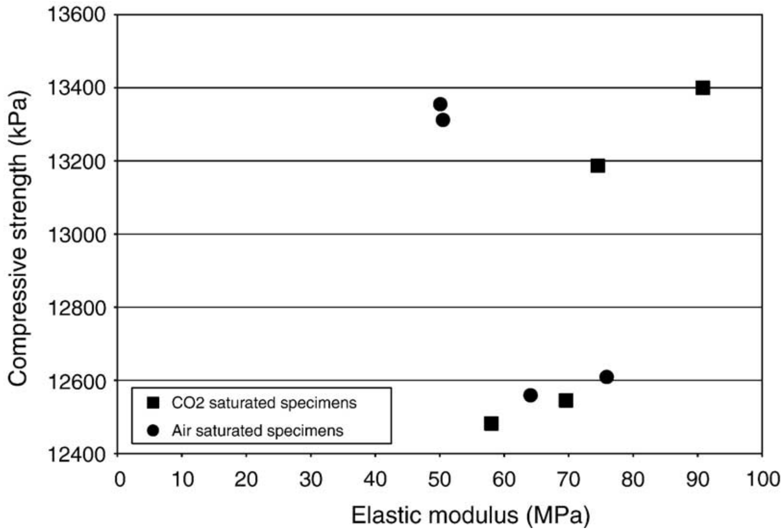

Fig. 10. Compressive strength vs. elastic modulus plots for CO_2- and air-saturated triaxial specimens.

data points for the CO_2- and air-saturated specimens in Fig. 10.

Fig. 11 compares the triaxial loading response of CO_2-saturated and air-saturated samples, tested at a fixed confining pressure of 10 MPa. Table 3 gives a summary of results for the triaxial testing.

Unlike the results obtained from uniaxial testing, the triaxial test results showed no significant change in either the strength or the elastic modulus of the brown coal with CO_2 saturation at a confining pressure of 10 MPa and an internal gas pressure of 2.0 MPa. The absence of a strength or elastic modulus decrease for triaxial specimens with CO_2 adsorption may be associated with confining stress related modifications to the adsorptive behaviour of CO_2 on brown coal, as observed by Larsen (2004) and Mastalerz et al. (2004), with CO_2 adsorption causing a greater surface energy decrease at smaller confining pressures than at larger ones, possibly having no effect at confining pressures as great as 10 MPa. Alternatively, the reason for no observed strength difference between air-saturated and CO_2-saturated specimens in the triaxial testing program may be related to inconsistencies in the testing methodology. The saturation period used in the testing

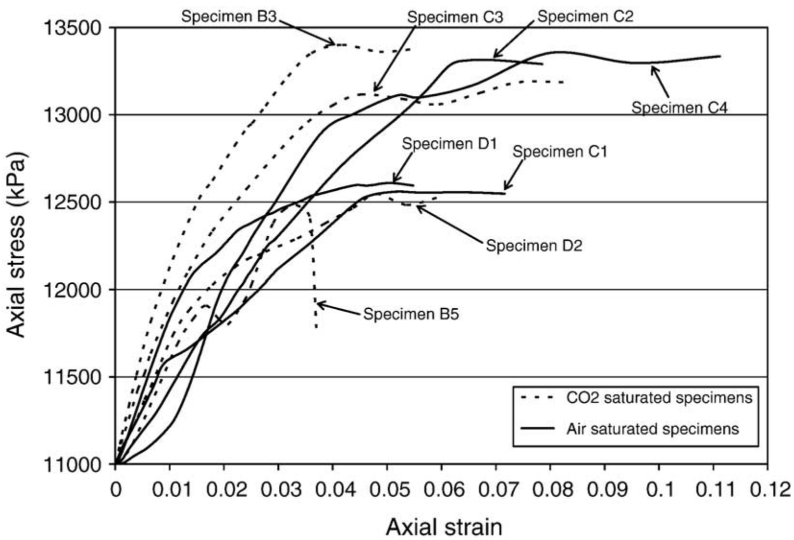

Fig. 11. Comparison of stress–strain behaviour for CO_2- and air-saturated triaxial specimens.

Table 3
Summary of triaxial test results

Specimen	Saturation gas	Triaxial compressive strength (kPa)	Elastic modulus (MPa)	Moisture content (% wb)
C1	Air	12559	64.1	62.2
C2	Air	13312	50.5	60.6
C4	Air	13355	50.1	62.3
D1	Air	12609	75.9	62.2
B3	CO_2	13400	90.8	Not measured
B5	CO_2	12482	58.0	Not measured
C3	CO_2	13187	74.5	57.2
D2	CO_2	12545	69.6	62.9

may not have been sufficient to allow significant adsorption of CO_2 for higher confining pressures and, thus, no adsorptive weakening was seen at 10 MPa of confinement. On the other hand, problems may have been caused by variability of the coal used for the triaxial tests. Coal, particularly low rank coal, is an extremely variable material that can differ substantially over small distances, with differing organic source components (e.g. varying amounts of woody material, leaf litter). The uniaxial testing was carried out using specimens all sourced from the same sample block. Due to sample block size restrictions, the same control over specimen variability could not be achieved for the triaxial test specimens and rather than all being from a single sample block, triaxial test specimens were sourced from three separate sample blocks. Hence, variability in the character of the brown coal specimens cored from different sample blocks may have compensated for a real strength decrease in the brown coal due to CO_2 adsorption. Uncertainty in the reason for the negligible strength decrease observed with CO_2 adsorption may be resolved by further triaxial testing, possibly using a more uniform sample set.

3.3. Flow testing during a triaxial test

Flow measurements recorded for one specimen (C3) during the stress–strain process revealed an initial decrease in CO_2 flow with increasing axial strain, to a minimum value. Following sample failure, a significant increase in CO_2 flow was observed, gradually decreasing back to moderate values. The trend of these results appears to reflect initial pore closure and a related permeability decrease with increasing axial pressure, followed by a period of minimal gas flow through the specimen. The sudden increase in CO_2 outflow is thought to be associated with a fracture permeability increase after failure, and the final gradual decrease is believed to be related to closure of the cracks formed at failure under continued axial loading. Small bumps during the fracture closure stage may be related to minor crack extension or episodes of movement along existing cracks under continued loading. These results agree with the findings of Somerton et al. (1975) and Wang and Park (2002) for the flow behaviour of porous materials during the stress–strain process. A plot of coal-CO_2 permeability during triaxial testing is shown in Fig. 12.

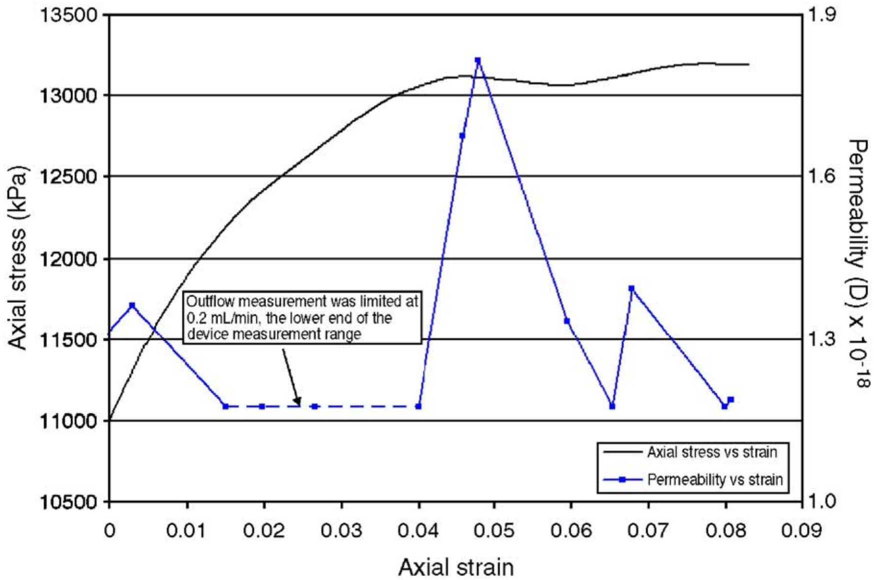

Fig. 12. Coal-CO_2 permeability of sample C3 during the stress–strain process.

The film flow meter used for recording the CO_2 flow during the stress–strain process has a minimum allowable measurement of 0.2 mL/min. In the testing period interpreted as the pore closure phase, outflows read a minimum value of 0.2 mL/min, though flows may have decreased to levels a significantly lower than 0.2 mL/min. This limitation in measurement prevented exact quantification of the effect of fracturing on the CO_2 permeability characteristics of the coal. Furthermore, difficulties with the liquid collection system at the time of testing prevented quantification of water flows during testing.

3.4. Implications for coal seam CO_2 sequestration

If the lack of a geomechanical response of the brown coal to CO_2 saturation under triaxial conditions was not related to problems in the testing procedure, it is anticipated that the hypothesised adsorptive weakening of coal by the introduction of CO_2 would not proceed under the lithostatic pressures expected for coal seam CO_2 sequestration. However, further testing is required to determine whether this apparent lack of an effect of CO_2 saturation on the strength and elastic modulus of brown coal was actually related to a deficient testing process. Permeability testing demonstrated an increase in CO_2 permeability in brown coal with fracturing and thus it is shown that fracturing presents an issue to be considered in coal seam CO_2 sequestration.

In applying the results of this study to assess the feasibility of coal bed CO_2 sequestration, a number of issues must be considered, including: the influence of CO_2 on the geomechanical behaviour of coal at the confining and injection pressures expected for the sequestration process; the influence of coal properties (rank, moisture content, etc.) on the adsorptive weakening of coal; whether the predicted CO_2-related strength reduction is significant enough to initiate fracturing under existing lithostatic (and tectonic) stresses, and knowledge of the magnitude of CO_2 permeability increase expected upon fracturing and whether this permeability increase will undermine the process of CO_2 retention in coal.

4. Conclusion

A surface energy decrease with the adsorption of CO_2 according to Gibbs' Adsorption Equation (Gibbs, 1921) will cause a decrease in the strength of coal by Griffith's criteria (Griffith, 1921). The results of a number of experimental studies carried out to explore the effect of CO_2 adsorption on the strength of coal overwhelmingly suggest an association between the presence of CO_2 in coal and the strength of coal. A fracture-related increase in the permeability of a porous medium such as coal will cause an increase in flow according to Darcy's law. Thus, according to theory and previous work, the introduction of CO_2 to a coal seam in the sequestration process will weaken the coal, possibly inducing fracture under regional and localised in situ stresses and allowing greater flow of CO_2 through the coal. Improved flow through the coal may undermine the role of the coal in sequestering carbon dioxide.

The results of the uniaxial testing provide evidence to suggest that the adsorption of CO_2 causes a decrease in both the unconfined compressive strength and the elastic modulus of brown coal. From the results, which represent an initial foray into experimental work on the topic, decreases in the unconfined compressive strength and the elastic modulus of brown coal on the order of 13% and 26%, respectively, are expected with the adsorption of CO_2. From the results of the triaxial testing, it was not clearly observed that the adsorption of CO_2 has the same effect on brown coal geomechanics with substantial confinement. Carbon dioxide flow and hence permeability during the stress–strain process decreased initially with pore closure but then increased significantly from its initial value with fracturing of the coal specimen.

Acknowledgements

The authors would like to thank Mr. Mike Leach of the Geomechanics Laboratories at Monash University for his help with the experimental work and Mr. Bill Wood of Yallourn Energy for supplying the coal used in the testing.

References

Ates, Y., Barron, K., 1988. The effect of gas sorption on the strength of coal. Min. Sci. Technol. 6 (3), 291–300.

Aziz, N.I., Ming-Li, W., 1999. The effect of sorbed gas on the strength of coal. Geotech. Geolog. Eng. 17 (3–4), 387–402.

Beamish, B.B., Crosdale, P.J., 1998. Instantaneous outbursts in underground coal mines: an overview and association with coal type. Int. J. Coal Geol. 35 (1–4), 27–55.

Brockway, D.J., Higgins, R.S., 1991. Brown coal sampling, analysis and composition. In: Durie, R.A. (Ed.), The Science of Victorian Brown Coal: Structure, Properties and Consequences for Utilisation, vol. 1. Butterworth-Heinemann Ltd, Oxford, pp. 1–43.

Czapliński, A., Holda, S., 1982. Changes in mechanical properties of coal due to sorption of carbon dioxide vapour. Fuel 61 (12), 1281–1282.

Dollimore, D., Heal, G.R., 1961. The effect of various vapours on the strength of compacted silica. J. Appl. Mech. 11 (12), 459–463.

Dollimore, D., Dollimore, J., Nowell, D.V., 1965. The porous nature of powdered coal and its relation to strength. Fuel 44 (4), 387–394.

Ettinger, I.L., Lamba, E.G., 1957. Gas medium in coal-breaking processes. Fuel 36 (3), 298–306.

Gibbs, J.W., 1921. On the equilibrium of heterogeneous substances. The Collected Works of J. Willard Gibbs, vol. 1. Yale University Press, New Haven, pp. 55–353.

Griffith, A.A., 1921. The phenomenon of rupture and flow in solids. Philos. Trans. R. Soc. Lond. 221 (587), 163–198.

Holdgate, G.R., 2003. Coal: world-class energy reserves without limits. In: Birch, W.D. (Ed.), Geology of Victoria. Victoria Division, Geological Society of Australia, Melbourne, pp. 489–516.

Lama, R.D., Bodziony, J., 1996. Outbursts of Gas, Coal and Rock in Underground Coal Mines. R.D. Lama and Associates, Wollongong.

Lama, R.D., Bodziony, J., 1998. Management of outburst in underground coal mines. Int. J. Coal Geol. 35 (1–4), 83–115.

Larsen, J.W., 2004. The effects of dissolved CO_2 on coal structure and properties. Int. J. Coal Geol. 57 (1), 63–70.

Mastalerz, M., Gluskoter, H., Rupp, J., 2004. Carbon dioxide and methane sorption in high volatile bituminous coals from Indiana, USA. Int. J. Coal Geol. 60 (1), 43–55.

Orowan, E., 1944. The fatigue of glass under stress. Nature 154 (3906), 341–343.

Somerton, W.H., Soylemezoglu, I.M., Dudley, R.C., 1975. Effect of stress on permeability of coal. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 12 (5–6), 129–145.

Viete, D.R., Ranjith, P.G., Kodikara, J., Xue, Z., 2005. The effects of CO_2 on the geomechanical behaviour of brown coal: uniaxial testing. Paper presented at the 40th Symposium on Rock Mechanics (USRMS) Anchorage, Alaska.

Vinokurova, E.B., Bogomolova, L.I., Ketslakh, A.I., Kontorovich, S. I., 1988. Crushing of gas-saturated anthracites. Colloid J. USSR 50 (1), 112–114.

Wang, J.-A., Park, H.D., 2002. Fluid permeability of sedimentary rocks in a complete stress–strain process. Eng. Geol. 63 (3–4), 291–300.