Chapter 3

Challenges and issues for CO$_2$ storage in deep coal seams

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Abstract: Global warming is one of the most critical environmental issues facing the world today, and according to scientific reports, ignoring this issue will lead to severe economic and environmental costs to society. The increased greenhouse gas concentration in the atmosphere is the major cause of global warming, and the effect of CO$_2$ is critical. It is therefore necessary to use a rational combination of all the possible CO$_2$ mitigation strategies, such as the use of renewable fuels, improved energy efficiency, carbon sequestration and increased conservation to achieve a safer CO$_2$ level in the atmosphere with the rapidly increasing emissions. CO$_2$ sequestration is considered here.

CO$_2$ sequestration involves the capture of CO$_2$ released from anthropogenic sources and its secure storage in deep underground locations, either off- (ocean sequestration) or on-shore (geo-sequestration). However, in terms of safety, reliability and cost, onshore sequestration is more effective than offshore sequestration. Of the various potential CO$_2$ storage sinks in deep underground (e.g. depleted oil and gas fields, saline aquifers, shale beds and coal mines), CO$_2$ storage in deep coal seams offers unique advantages over the others, and the potential for offsetting CO$_2$ sequestration costs by producing a valuable energy product such as methane (coal seam gas). For nearly 20 years, CO$_2$ has been injected into coal seams to enhance the recovery of methane in a process known as enhanced coal bed methane (ECBM) recovery.

However, adsorption of the injected CO$_2$ into the coal mass causes it to swell, causing significant alterations in its internal rock mass structure, resulting in major modifications to its flow and strength properties. This CO$_2$ adsorption-induced coal matrix swelling process is dependent on the properties of both the seam and the injected CO$_2$, and swelling is reduced with increasing temperature due to the reduced sorption capacity. Furthermore, swelling exhibits inverted-U shaped variation with coal maturity or rank, due to the corresponding variation of the coal mass properties such as moisture, carbon content and pore space. On the other hand, the extent of swelling is largely dependent on the pressure and the physical state of the injected CO$_2$, and super-critical CO$_2$ creates much greater swelling than gas or liquid CO$_2$ due to its higher chemical potential. In addition, high-pressure injection of CO$_2$ causes the swelling process to be enhanced due to the higher flow ability of the injected CO$_2$ under reduced effective stress conditions at increased injection pressures. However, potential coal seams for CO$_2$ sequestration are available at extremely deep locations and there is a high possibility of phase change from gas/liquid to the super-critical state in the underground environment owing to changes in field conditions. This confirms the likely occurrence of high swelling rates in deep coal seams with CO$_2$ injection.
The effectiveness of the CO\textsubscript{2} storage process in any coal seam is greatly influenced by the flow ability of the injected CO\textsubscript{2} through the seam, which is dependent on a number of factors. These factors include i) coal matrix swelling that causes the internal coal seam pore space available for fluid/gas movement to be reduced, ii) CO\textsubscript{2} injecting pressure and seam depth, both of which change the effective stress on the coal seam and eventually, the seam's pore space, and iii) seam temperature that creates thermal expansion in the seam and leads to reduced sorption capacity with kinetic energy increment in injected CO\textsubscript{2} molecules. Importantly, the injected CO\textsubscript{2} phase condition critically influences its flow behavior in the seam, and super-critical, the form of CO\textsubscript{2} expected in deep coal seams, has significantly lower permeability than gas/liquid CO\textsubscript{2}, which causes unpredictable CO\textsubscript{2} injectibility into deep coal seams. Reduction of seam permeability over time after CO\textsubscript{2} injection is a common issue faced by many field-scale CO\textsubscript{2} sequestration projects. For example, there was around 50\% reduction in CO\textsubscript{2} injectivity at the Allison unit CO\textsubscript{2} sequestration project in the San Juan basin, USA, during the first two years of injection.

Secure storage of injected CO\textsubscript{2} in the seam is critically important in CO\textsubscript{2} geo-sequestration in deep coal seams in terms of environmental safety and health. It is important to prevent the upward migration of CO\textsubscript{2}, as this has potential to cause distress and on occasion death, and lateral migration into aquifers and surrounding more permeable geologic strata. These factors are mainly dependent on the coal mass strength properties. However, the fact that CO\textsubscript{2} adsorption-induced swelling creates a weakening effect in deep coal seams is well known. This strength reduction is greatly dependent on injecting CO\textsubscript{2} phase and pressure, it increases with increasing pressure, and super-critical CO\textsubscript{2} causes much greater strength reduction than gas/liquid CO\textsubscript{2}. Furthermore, CO\textsubscript{2} adsorption into any coal seam mainly occurs through the walls of its natural cleat system that were formed during the coalification process. High rank coal seams, located deeper underground, are therefore likely to be subjected to a higher strength reduction with CO\textsubscript{2} injection, offering more numerous loci for CO\textsubscript{2} adsorption. However, it is generally accepted that the deeper the seam, the more secure the CO\textsubscript{2} storage. On the other hand, the likely super-critical nature of CO\textsubscript{2} in deep coal seams also causes greater strength reduction with CO\textsubscript{2} injection.

Existing government policies, public perceptions, and strict rules on coal mining affect the implementation of CO\textsubscript{2} sequestration in deep coal seams. For example, mines are generally required to have a maximum 3\% CO\textsubscript{2} by volume in the mine air, and therefore injection of CO\textsubscript{2} into coal seams causes the mining environment to be polluted by the injected CO\textsubscript{2} and eventually, the seams become unsafe to mine forever. The current lack of knowledge related to coal seam CO\textsubscript{2} sequestration severely affects the implementation of this process in potential coal seams around the world. The complex heterogeneous nature of coal, which creates location-dependent coal seam properties, is the main reason for the limited knowledge of coal CO\textsubscript{2} sequestration.

I INTRODUCTION

1.1 Global warming and the greenhouse gas effect

Emissions of greenhouse gasses (GHGs) will increase the average global temperature by 1.1 to 6.4 °C by the end of the 21\textsuperscript{st} century (Pachauri & Reisinger, 2007) and exceeding
the current global average temperature by more than 2 °C would lead to serious consequences. Therefore, the International Panel on Climate Change (IPCC) has warned of the need for a 50-80% global GHG emissions reduction by 2050.

Carbon dioxide (CO₂) is one of the most significant greenhouse gases, and the anthropogenic CO₂ content (the CO₂ generated due to human activities) in the atmosphere is critical. In particular, the burning of fossil fuels such as coal, oil, and gas has caused a substantial increase in the concentration of CO₂ in the atmosphere (Borah et al., 2011; Pachauri & Reisinger, 2007; Perera & Ranjith, 2012; Ranathunga et al., 2014; Stangeland, 2007; White et al., 2005). According to Sundquist et al. (2003) this increase in atmospheric CO₂ concentration from around 280 to more than 380 ppm over the last 250 years has caused measurable global warming. The potential adverse impacts of global warming are sea-level rises; increased frequency and intensity of wildfires, floods, droughts, and tropical storms; changes in the amount, timing, and distribution of rain, snow, and run-off; and the disturbance of coastal marine and other ecosystems. Rising atmospheric CO₂ is also increasing the amount of CO₂ absorbed by seawater, causing the ocean to become more acidic, which potentially disruptively affects marine plankton and coral reefs (Sundquist et al., 2008).

At the 16th United Nations Framework Convention on Climate Change (UNFCCC), held in Cancun, Mexico in 2010, the participants including Australia agreed to commit to a maximum temperature rise of 2 °C above pre-industrial levels, and to consider lowering that maximum to 1.5 degrees in the near future. Therefore, it is imperative to investigate possible CO₂ mitigation options and to implement them as soon as possible.

Some of the possible CO₂ mitigation options are carbon dioxide capture and storage or sequestration (CCS), energy efficiency improvements, the switch to less carbon-intensive fuels, nuclear power, renewable energy sources, enhancement of biological sinks, and reduction of non-CO₂ greenhouse gas emissions (Stangeland, 2007; Sundquist et al., 2008; White et al., 2005). Of those methods, CCS has the potential to reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reductions (Gale, 2004; Metz et al., 2005; Perera & Ranjith, 2012; White et al., 2005).

1.2 CO₂ sequestration

Before human-caused CO₂ emissions began the natural processes that make up the global “carbon cycle” (see Figure 1), a near balance was maintained between the uptake of CO₂ and its release back to the atmosphere. However, existing CO₂ uptake mechanisms (sometimes called CO₂ or carbon “sinks”) are insufficient to offset the accelerating pace of emissions related to human activities (Sundquist et al., 2008). According to Sundquist et al. (2003), annual carbon emissions from burning fossil fuels in the United States are about 1.6 Gigatons, whereas annual uptake amounts are only about 0.5 Gigatons, resulting in a net release of about 1.1 Gigatons per year. Hence, controlling atmospheric CO₂ will require deliberate mitigation with an approach that combines reducing emissions and increasing storage.

CCS basically means the removal of CO₂ directly from anthropogenic sources (capture) and its disposal in geological or oceanic media, either permanently (sequestration), or for geologically significant time periods (storage) (Benson & Cole, 2008). The term “carbon sequestration” is used to describe both natural and deliberate processes by which CO₂ is either removed from the atmosphere or diverted from
emission sources and stored in the ocean, terrestrial environments (vegetation, soils, and sediments), and geologic formations. With over 60% of worldwide emissions coming from point sources that are potentially amenable to CO$_2$ capture, the prospects for CCS to significantly reduce CO$_2$ emissions are great (Sundquist et al., 2008). Technical and economic assessments suggest that over the coming century, CCS may contribute up to 20% of CO$_2$-emission reductions, equivalent to the reductions expected from efficiency improvements and large-scale deployment of renewable energy resources (Benson & Cole, 2008; Metz et al., 2005). Therefore, CO$_2$ sequestration becomes a more promising solution for the required outcomes of The United Nations Framework Convention on Climate Change (UNFCCC).

To significantly reduce global emissions to pre-industrial levels, huge volumes of CO$_2$ must be sequestered. For example, a large coal-fired power plant emits about 8 million tons of CO$_2$ annually. At the pressures and temperatures expected for sequestration reservoirs, the volume required to sequester CO$_2$ as a super-critical fluid is about 10 million cubic meters (Mm$^3$) per year. According to existing studies (Bachu, 2003; Benson & Cole, 2008; Metz et al., 2005; Perera & Ranjith, 2012; Sundquist et al., 2008; White et al., 2005), several methods can be used in sequestrating CO$_2$, mainly on-shore and off-shore.

### 1.2.1 Off-shore CO$_2$ sequestration

Injecting CO$_2$ into off-shore marine sediments is one potential approach to the sequestration of CO$_2$ (see Figure 2), in which the CO$_2$ injected into off-shore sediments is stored deep beneath the ocean, avoiding the threats of direct ocean injection and effects on ocean ecology. There are several advantages in off-shore CO$_2$ sequestration compared to on-shore CO$_2$ sequestration. According to House et al. (2006), CO$_2$ is denser than seawater below 3000 m; therefore, off-shore reservoirs with suitable permeability in deep seawater make the cap rock less significant. Furthermore, marine sediments offer

![Figure 1: Global carbon cycle (Benson & Cole, 2008).](image)
large storage potential. For example, the cretaceous sandstones of New Jersey have the capacity to store at least several hundred billion tons of CO$_2$, which is enough to dispose of all the CO$_2$ from power plants within 250 km of the coast near the reservoir for the next century (Schrag, 2009). Another advantage of off-shore CO$_2$ storage is the ability to manage pressure within the geologic formation by drilling additional wells to release pore fluid to the ocean, which avoids injected CO$_2$ back-migration to the atmosphere by the prevention of fractures (Archer & Brovkin, 2008). Moreover, the released pore fluid is similar to seawater, unlike the pore fluid released from on-shore CO$_2$ sequestration, and is more environmentally friendly (Vaughan & Lenton, 2011).

Although off-shore CO$_2$ sequestration acts as a large anthropogenic CO$_2$ storage pool, some researchers (Adams & Caldeira, 2008; Drange et al., 2001; Sabine & Tanhua, 2010) have found a number of challenges in this process. In relation to the lack of secure storage life, high operational and transportation costs (most off-shore sites are located far away from the CO$_2$ trapping points) there are many environmental concerns, such as ocean acidification. Therefore, based on economic factors, the storage life and availability of sites, on-shore CO$_2$ sequestration has been identified as the most viable solution to the problem.

### 1.2.2 On-shore CO$_2$ sequestration

Another option to reduce anthropogenic CO$_2$ emissions to the atmosphere is to capture and store the CO$_2$ in porous rock masses (sedimentary rocks) available deep under the surface. Globally, the CO$_2$ storage capacity in sedimentary rocks is quite high, and recent estimates for the U.S. alone show a potential storage capacity of 2020 to 14,220 Gigatons of CO$_2$ (GtCO$_2$) (Orr, 2009). Depths below 800 to 1000 m, where the CO$_2$ density is high enough (500 to 700 kg/m$^3$) to limit the storage volume, are suitable for on-shore CO$_2$ sequestration. In this technique, the presence of low-permeability formations called cap rock above the storage zone is crucial in order to prevent the back-migration of stored CO$_2$ into the atmosphere (Ranjith & Perera, 2012).
Oil and gas reservoirs are one potential choice for on-shore CO₂ sequestration (see Figure 2). For example, for the purpose of enhanced oil recovery (EOR), around 30 megatons of CO₂ (MtCO₂) are injected into oil reservoirs in west Texas each year (Sundquist et al., 2008). The potential for fuel recovery to offset the sequestration cost and the already available underground and surface infrastructure (wells, equipment and pipelines) make this method more attractive (Orr, 2009).

Injection of CO₂ into deep saline formations (see Figure 2) is also being tested on a commercial scale. CO₂ is typically in its super-critical phase at sub-surface temperatures and pressures, which is more dense than natural gas but less dense than brine or oil. The injected CO₂ interacts with the fluids and minerals present in the saline aquifers. CO₂ is relatively soluble in brine, and the resulting brine mixture is slightly denser than brine alone. Further, under typical sub-surface conditions, CO₂ is dissolved in brine at a proportion of 1:20 (CO₂: brine) by volume (Stevens et al., 2001). Once a larger volume of CO₂ is dissolved, the driving force for upward migration of CO₂ is eliminated, and the CO₂ is immobilized while it continues to dissolve slowly, which will continue for a time scale of centuries (Bachu, 2000).

Deep unmineable coal seams are also possible storage locations, with international coal bed methane resources of 3010–7840 trillion cubic feet (Orr, 2009). When CO₂ is injected into coal seams, it adsorbs into the coal matrix and then desorbs the methane (CH₄) (developed during the coalification process) which migrates to the fractures and can be recovered. This process is known as enhanced coal bed methane (ECBM) recovery (Orr, 2009; Ranathunga et al., 2014; White et al., 2005). ECBM recovery is further discussed in the following sections.

2 CO₂ SEQUESTRATION IN DEEP COAL SEAMS

Coal is formed from the biodegradation of buried plants, and the process of forming coal from buried plants subjected to burial pressure and temperature is called the coalification process. Naturally-formed coal is composed of a solid matrix with well-defined networks of natural fracture systems called cleats, which formed during the coalification process. Therefore, the more mature the coal mass, the more developed the cleat system. Depending on the degree of coalification, coal can be categorized into several ranks, mainly high rank (bituminous coal and anthracite) and low rank (lignite and sub-bituminous coal), and rank increases with increasing coal maturity. Coal is composed of carbon (50%–98%), hydrogen (3%–13%), oxygen and smaller amounts of other elements, and the composition is dependent on the coal rank (see Table 1).

<table>
<thead>
<tr>
<th>Coal rank</th>
<th>Carbon (*db %)</th>
<th>Volatile matter (*db %)</th>
<th>Moisture content (%)</th>
<th>Specific energy (*db kJ g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>60–75</td>
<td>45–55</td>
<td>50–70</td>
<td>25–30</td>
</tr>
<tr>
<td>Sub-bituminous</td>
<td>75–80</td>
<td>40–45</td>
<td>25–30</td>
<td>28–32</td>
</tr>
<tr>
<td>Bituminous</td>
<td>80–90</td>
<td>20–40</td>
<td>5–10</td>
<td>30–35</td>
</tr>
<tr>
<td>Anthracite</td>
<td>90–95</td>
<td>5–7</td>
<td>2–5</td>
<td>35–38</td>
</tr>
</tbody>
</table>

Note: *db – dry basis
example, high rank coal has greater carbon content than low rank coal. Generally, coal can be mainly separated into brown coal (lignite) and black coal (bituminous), depending on the carbon content (see Figure 3). According to Miedzinska et al. (2013), the characteristic surface morphology of a coal sample normally appears to be granular structure under scanning electron microscopy (SEM). There are many slots and free spaces between the grains with abundant storage of methane. Due to its chemical properties, coal has a greater affinity to absorb CO$_2$ than other gases like methane (CH$_4$) and nitrogen (N$_2$). This provides the basis for the CO$_2$ sequestration process to be on-going (White et al., 2005).

2.1 Why store CO$_2$ in deep coal seams?

According to Shi et al. (2014), gases are stored in coal beds by three mechanisms:

- physically adsorbed compounds on the internal surfaces of coal
- adsorbed within the molecular structure; and
- within pores and natural structures.

Around 98% of CO$_2$ exists in an adsorbed phase on the walls of coal’s micro pores, while the rest remains as free gas inside the cleats (Battistutta et al., 2010; Perera & Ranjith, 2012; Shi & Durucan, 2005; White et al., 2005). Therefore, CO$_2$ exists in a more stable form in coal, which will eventually decrease the risk of back-migration (Shi & Durucan, 2005). Moreover, during the coalification process, a large amount of methane (CH$_4$) is formed. When CO$_2$ is injected into a coal seam, it improves the recovery of CH$_4$ by directly displacing the methane from the coal, or by lowering the effective partial pressure of the CH$_4$ (Harpalani & Schraufnagel, 1990). This phenomenon is known as enhanced coal bed methane (ECBM) recovery, which will eventually offset the cost of sequestration of CO$_2$. Figure 4 illustrates a schematic diagram of the ECBM process.

Since coal has a larger surface area associated with the micro-pore structure compared with the conventional reservoirs of a given volume of rock, it can store...
a substantial amount of CO$_2$ within the pore spaces (Perera & Ranjith, 2012; Stevens et al., 2001). For example, the combined Bowen and Sidney basins in eastern Australia can store about 11.2 gigatons of CO$_2$ (Stevens et al., 2001). According to Harpalani & Schraufnagel (1990), 5-15 gigatons of CO$_2$ in the world can be sequestered in coal beds by the profits gained from CH$_4$ production through the ECBM recovery process. These details demonstrate the prospective importance of CO$_2$ sequestration in deep unminable coal seams.

2.2 What happens when CO$_2$ is injected into coal seams?

As mentioned above, in coal beds, most gases exist in an adsorbed phase in the coal matrix and some as free gas in the fracture pore space. Generally, the coal mass natural cleat system formed during the coalification process governs gas movement through the coal matrix, unless a large joint exists (White et al., 2005). In the gas transport process in coal, first it moves through its natural cleat system and then adsorbs into the coal.

![Enhanced coal-bed methane recovery process.](image-url)
matrix along the cleat walls (White et al., 2005) (see Figure 5). When the gas molecules reach the micro pores in the coal matrix, they follow the diffusion process (see Figure 5), as the mean flow path of the gas molecules is greater than the micro pore diameter. In contrast, when the gas molecules reach the cleats, flow is controlled by the coal mass permeability (Darcy flow), as the mean flow path of the gas molecules is smaller than the cleat width. However, the diffusion process is quite a slow process, and it therefore takes much greater time than the pressure-driven advection process in cleats.

According to existing findings, both CO₂ sequestration and ECBM recovery are dependent on the coal mass and adsorbing gas properties, such as coal rank, moisture content, temperature, depth, existing gas composition and adsorbing gas pressure, gas type and phase, and injection and production well operations (Gilman & Beckie, 2000; Perera & Ranjith, 2012; Sawyer et al., 1990). Laboratory isotherm measurements demonstrate that medium- to high-rank coal can adsorb approximately twice as much CO₂ by volume as CH₄, and the common assumption is that, for higher rank coals, the ECBM process stores 2 moles of CO₂ for every mole of CH₄ desorbed (White et al., 2005). However, some researchers have determined that some low rank coals may adsorb as much as 10 moles of CO₂ for every mole of CH₄ (Ranathunga et al., 2014). Vishal et al. (2013) investigated the feasibility of CO₂ driven ECBM recovery in Indian coals (coal type – black coal) using a field-scale numerical model. These researchers found that approximately three times the volume of CO₂ can be sequestered in place of every volume of CH₄ for high rank coals. Field applications and laboratory experiments have shown that this ratio could be even larger at depths greater than 800 m, where gaseous CO₂ changes to super-critical CO₂ (White et al., 2005).

However, according to Viete & Ranjith (2006), the injection of CO₂ into coal causes its chemical and physical properties to be greatly changed, resulting in unpredictable amounts of injectable CO₂ and producible CH₄ in coal seams. There has been much research conducted on this process, which has revealed that a great degree of swelling is
caused by CO$_2$ adsorption into the coal matrix that, in turn, can cause the permeability and the overall strength of the coal mass to be severely decreased (Fujioka et al., 2010; Jasinge et al., 2011; Perera & Ranjith, 2012; Wang et al., 2011).

### 3 COAL MATRIX SWELLING

Coal matrix swelling occurs due to the lowering of the surface energy of the coal with gas adsorption. The decreased surface energy has the effect of lessening the strength of the chemical bonding in the atomic structure of the matrix, resulting in a volumetric expansion, or swelling, of the coal. Due to the fact that CO$_2$ adsorption is much greater than CH$_4$ and N$_2$ due to its higher chemical potential and adsorption capacity, the coal mass tends to swell significantly during CO$_2$ injection (Viete & Ranjith, 2006). According to Day et al. (2010), the amount of swelling in coal is directly related to the absolute adsorption capacity (Equation 1).

\[
V_s = -0.0037 + 0.1596V_{abs} + 0.0101V_{abs}^2
\]  

(1)

where $V_s$ is the volumetric swelling percentage and $V_{abs}$ is the volume of the absolute adsorption. Meanwhile, there is a direct relationship between amount of matrix shrinkage and desorbed gas volume at the standard pressure (Harpalani & Chen, 1995) (Equations 2 and 3).

\[
\varepsilon_v = C \left( \frac{V_{LP}}{P_{L+P}} \right)
\]  

(2)

\[
V_{des} = \left( \frac{V_{LP}}{P_{L+P}} \right)
\]  

(3)

where $\varepsilon_v$ is the volumetric strain of the coal matrix; C is a constant depending on the coal mass properties; $p$ is the pore pressure; $V_{des}$ is the volume of gas desorbed from the coal matrix.

It should be noted that swelling does not occur homogeneously throughout the coal structure, but rather occurs more readily in the organic regions (macerals), which causes compression of the inorganic regions (minerals) of the matrix (Day et al., 2010). This is due to the strength of the bonding within the minerals being much greater than that between the organic molecules within the coal matrix. According to Majewska et al. (2009), the degree of swelling is dependent on the moisture content, whereas the megascopic texture controls the swelling behavior with respect to bedding orientation. It has been noted that the degree of swelling is greater in a direction perpendicular to the bedding plane of the coal matrix than parallel to the plane (Karacan, 2007). This is caused by the heterogeneity of swelling between the organic and inorganic components within the coal matrix. As a result of this, and the inherent weaknesses found along bedding planes, it has been shown that cracks more readily develop along the face cleats, as opposed to across the bedding planes along the butt cleats (Anggara et al., 2014). As mentioned previously, swelling of the coal matrix would definitely break the natural balance of the structure, with direct influences on permeability and strength reduction, which are the key factors in the CO$_2$ sequestration process.
3.1 Effective factors for CO$_2$ injection-induced coal matrix swelling

According to previous studies (Czapliński & Holda, 1982; Day et al., 2010; Deevi & Suuberg, 1987; Jasinge et al., 2011; Majewska & Ziȩtek, 2007; Shi & Durucan, 2005), seam properties (coal rank and temperature) and injecting CO$_2$ properties (injecting CO$_2$ phase and pressure) are some effective factors for coal matrix swelling. These are therefore discussed in the following sections.

3.1.1 Seam properties

a) Coal rank

In general, the deeper the coal seam, the higher the rank, and this explains the effect of coal seam location on the CO$_2$ sequestration process. However, some contradictions can be seen in the research findings on the effect of coal rank on its swelling. Reucroft & Sethuraman (1987) found that there is an inverse correlation between coal rank and matrix swelling; high rank coal undergoes less swelling than lower-ranking coal under the same environmental conditions. These results have been confirmed by Ceglarska-Stefańska & Czapliński (1993) (see Figure 6).

Figure 6 Effect of seam properties on swelling (Bae & Bhatia, 2006; Ceglarska-Stefańska & Czapliński, 1993; Jasinge et al., 2012; Perera et al., 2011; Reucroft & Sethuraman, 1987; Walker et al., 1988).
This is thought to be due to the less mobile polymers present in high-ranking coal in contrast to low-ranking coal. This has the effect of preventing such a great deal of swelling at the molecular level, which transfers to less swelling present at the macromolecular level (Ceglarska-Stefańska & Czapliński, 1993). However, Walker et al. (1988) observed the increment only for lignite to highly volatile bituminous coals, and any further increase of rank causes the swelling effect to be reduced with increasing rank (in the anthracite region) (see Figure 6(a)).

b) Temperature

With increased temperature, gas adsorption capacity is reduced (Ceglarska-Stefańska & Czapliński, 1993), because with the temperature increment, gas molecules are released form the adsorbed phase as their kinetic energy is accordingly increased. According to Perera & Ranjith (2012), Bae & Bhatia (2006) and Kronimus et al. (2008), super-critical CO$_2$ is subjected to the temperature effect more significantly than sub-critical CO$_2$ (see Figure 6(b)). As discussed in the previous section, sorption capacity is directly proportional to the coal matrix swelling. Hence, similar behavior can be suggested for the temperature effect on swelling (Perera & Ranjith, 2012). According to the geothermal lines, underground temperature proportionally increases with depth. Therefore, according to both of these influences (rank and temperature), the CO$_2$ sequestration-created swelling effect should be clearly dependent on the location of the coal seam.

c) Depth (confining pressure)

When the depth is increased, CO$_2$ permeability in coal seams is reduced, since the pore space available for gas movement is shrunk considerably at greater depths, due to the higher confinement, resulting in higher tortuosity and consequently lower flow rate through the coal mass. This reduction of coal permeability for CO$_2$ causes less CO$_2$ adsorption into the coal matrix, resulting in less matrix swelling. This observation is irrelevant to coal rank, according to the studies by Jasinge et al. (2012) for brown coal (see Figure 6(c-i)) and Perera et al. (2011b) (see Figure 6(c-ii)), for bituminous coal. These studies reported similar observations of less coal matrix swelling at higher confinements.

### 3.1.2 Injecting CO$_2$ properties

Beyond 7.38 MPa pressure and 31.8°C temperature, CO$_2$ exists in its super-critical condition (see Figure 7) (Perera et al., 2011a; Vishal et al., 2013). It is well-known that the preferred coal seams for the ECBM production process are normally present beyond 1000 m from the ground surface, where the pressure and temperature are higher than the critical value of CO$_2$ (7.38 MPa and 31.8°C), and CO$_2$ is therefore present in the super-critical state (Figure 7). Therefore, Perera et al. (2011b) conducted a series of tri-axial experiments under sub-critical and super-critical CO$_2$ adsorption to investigate the CO$_2$ phase and pressure effect on coal swelling. They measured the radial strain increment in the coal samples during 15 hours of sub-critical and super-critical CO$_2$ adsorption, maintaining the system temperature above the critical temperature of CO$_2$ (31.8°C) (Figure 8(a)). According to the results, both sub-critical and
super-critical CO₂ adsorptions induce a considerable swelling in coal, and the swelling created by super-critical CO₂ adsorption is more than three times greater than sub-critical CO₂ adsorption-induced swelling (Figure 8(a)). This is probably due to the highly chemically reactive nature of super-critical CO₂ compared to sub-critical CO₂. This implies that un-mineable coal seams are more vulnerable to the swelling effect. The effect of CO₂ pressure on coal swelling has also been studied by Day et al. (2010), Harpalani & Chen (1995) and Pan & Connell (2006), who have confirmed the increment of swelling with CO₂ pressure (see Figure 8(b)). In addition, Day et al. (2010: Figure 8(b)) and Pan & Connell (2006: Figure 8(b)) described the behavior at high pressures, where the swelling ratio may decrease after reaching a maximum swelling.
Therefore, it is clear that not only gas injection pressure but also the adsorbing gas phase condition has a significant effect on coal matrix swelling.

4 CO₂ SEQUESTRATION EFFECT ON DEEP COAL-SEAM FLOW CHARACTERISTICS

Expansion of the coal matrix with swelling induced by CO₂ adsorption leads to the closure of cleats and fractures, as well as the reduction of the pore space available for gas movement, which eventually results in reduction of permeability. As the reduction of permeability would directly obstruct the injection of CO₂, it is necessary to have a comprehensive understanding of the process, to enable better control of CO₂ injection.

4.1 Does CO₂ sequestration create unpredictable CO₂ injectibilities?

Permeability is the term that provides a quantitative picture of the flow ability through any media. According to previous studies (Perera et al., 2011a; Perera & Ranjith, 2012; White et al., 2005), the permeability of natural coal seams varies with coal mass properties such as coal rank (carbon content and cleat structure), temperature and confining pressure, and injecting gas properties, such as phase and pressure.

Importantly, CO₂ injection into a deep coal seam causes its permeability to be altered, mainly due to CO₂ adsorption-induced coal matrix swelling. Existing research studies clearly show the significant swelling created by CO₂ injection into deep coal seams and the corresponding reduction of coal mass pore spaces and eventually the permeability (Viete & Ranjith, 2006; Perera et al., 2011b; Vishal et al., 2013). According to Perera et al. (2011a), this permeability reduction increases with increasing CO₂ injection pressure and CO₂ phase transition from sub- to super-critical (see Table 2). Moreover, as shown in Table 2, the temperature of the coal seam has a significant influence on the coal permeability alterations which occur with CO₂ injection, and CO₂ permeability in coal increases with increasing temperature only at higher CO₂ injection pressures (>10MPa). This is basically due to the fact that, with increasing temperature, the sorption capacity of and the swelling effect in coal are reduced, due to the increased kinetic movement of the CO₂ molecules (Bae & Bhatia, 2006), resulting in increased coal permeability at higher temperatures. This indicates the importance of selecting a coal seam with appropriate physical properties to achieve effective CO₂ sequestration in coal.

If the CO₂ sequestration process is considered, Durucan & Shi (2009) found some permeability reduction in deep coal seams due to methane adsorption. They also found that the reduction is partially recovered when permeability enhancement occurs with methane desorption (coal matrix shrinkage) during the CO₂ sequestration process. However, CO₂ creates much higher swelling effects in coal compared to methane or many other types of gas, and the effect is higher than the coal mass shrinkage effect during CH₄ desorption (Ranathunga et al., 2014). Therefore, the CO₂ sequestration process causes coal seam permeability to be significantly reduced over time. Therefore, the CO₂ sequestration process will require permeability enhancement treatments over time.
Table 2 Effect of CO₂ injection on coal seam permeability during CO₂ sequestration.

<table>
<thead>
<tr>
<th>Effective factor</th>
<th>Key observation</th>
<th>Figure</th>
</tr>
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</table>
| Coal rank        | - The CO₂ adsorption capacity is higher for high rank coal compared to low rank coal which leads to higher matrix swelling for higher rank coal and relatively lower permeability compared to low rank coal (Saghafi et al., 2007).  
- High rank coal has a higher surface area compared to low rank coal due to its cleat structure developed during the coalification process, which leads to higher adsorption capacities. | ![Variation of gas adsorption capacity in coal with pressure](image)  
(Saghafi et al., 2007)                                                                                                                     |
| Temperature      | - A significant increase in coal permeability can be observed with increasing temperature for higher CO₂ injection pressures (>10 MPa), and an insignificant effect on permeability at low CO₂ injection pressures (<9 MPa) (Perera & Ranjith, 2012)  
- Kinetic energy of gas molecules increases with increasing temperature. By the time the kinetic energy exceeds the intermolecular forces, the molecules tend to be released with random motion, which reduces the gas adsorption capacity in coal (Clarkson & Bustin, 1997). | ![Temperature effects on CO₂ permeability at 20 MPa confinement](image)  
(Perera & Ranjith, 2012)                                                                                                               |
### Table 2 (Cont.)

<table>
<thead>
<tr>
<th>Effective factor</th>
<th>Key observation</th>
<th>Figure</th>
</tr>
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<tbody>
<tr>
<td>Confining pressure</td>
<td>- Under the same experimental conditions, higher confining pressure induces lower permeability (Day et al., 2010; Perera et al., 2011a) &lt;br&gt;  - The compressive force created by higher confinements at greater depths causes the pore space available for gas movement to shrink considerably, resulting in higher tortuosity and consequently lower flow rate through the coal mass (Perera et al., 2011a).</td>
<td>![Permeability for CO₂ movement with confining pressure](Perera et al., 2011a)</td>
</tr>
<tr>
<td>CO₂ phase and pressure</td>
<td>- Permeability reduction increases with increasing CO₂ injection pressure and CO₂ phase transition from sub- to super-critical (Perera et al., 2011a; Shi &amp; Durucan, 2005). CO₂ tends to change from sub-critical to super-critical in deep coal seams with high temperature and pressure (approximately 7.38 MPa and 31.8°C) (see Figure 7) &lt;br&gt;  - A drastic increment in coal adsorption is observed after 7.38 MPa up to around 9 MPa, with an indication of CO₂ adsorption increase in super-critical state. &lt;br&gt;  - The transformation of sub-critical to super-critical phase leads to different thermo-physical and transport properties, which may also influence the sorption capacity (Wang et al., 2011). The greater swelling effect, as well as the higher increment in its viscosity, contribute to the high decline in permeability (Jasinge et al., 2010).</td>
<td>![Permeability for CO₂ movement with injection pressure](Perera et al., 2011a)</td>
</tr>
</tbody>
</table>
5 CO2 SEQUESTRATION EFFECT ON DEEP COAL SEAM MECHANICAL PROPERTIES

Not only CO2 injectibility into coal seams, also the overall strength of those seams is found to be altered with the CO2 injection process, which is a greater threat in terms of long-term safety of the CO2 storage process in deep coal seams as it may cause the back-migration of injected CO2 into the atmosphere. Therefore, it is of great importance to have a comprehensive understanding of the effect of CO2 sequestration to achieve better control of coal mass integrity during and after the CO2 sequestration process.

5.1 Does CO2 sequestration affect coal seam strength?

As proposed by Gibbs (1878) and Griffith (1921), material strength depends on the chemical potential of the adsorbate, and replacement of the existing adsorbate with one more chemically potent causes it to be weakened. CO2 is clearly a more chemically potent gas compared to pre-adsorbed methane in coal seams (Gibbs, 1878; Griffith, 1921). This implies that the replacement of the CH4 with CO2 injection causes the coal seam strength to be reduced. The natural coal mass structure is a glassy, strained and cross-linked macro-molecular structure with high energy, which limits the freedom of coal molecules to move, resulting in a highly brittle structure (Larsen et al., 1997; Majewska & Ziętek, 2007; Goodman et al., 2005). When CO2 is adsorbed, the coal mass polymer structure is rearranged with the increment of free volume in the coal matrix and the ductile properties of the coal structure are enhanced, affect the elastic modulus of the coal (Perera & Ranjith, 2012).

The reduction of coal strength with CO2 injection into it is well known, and this strength reduction varies with seam location and injecting CO2 properties (Aziz & Ming-Li, 1999; Czapliński & Holda, 1982; Day et al., 2010; Jasinge et al., 2011; Perera & Ranjith, 2012). For example, the CO2 adsorption-induced strength reduction is greater for high rank coal located at greater depths, and increasing the injecting CO2 pressure causes greater brittleness reduction in the coal seam. Table 3 illustrates the current findings on this issue.

Importantly, the CO2 sequestration and ECBM processes typically target deep coal deposits, and at such locations CO2 may not exist in a sub-critical phase, as it does under standard laboratory conditions, but instead exists in a super-critical state. Therefore, Karacan (2007) and Aziz & Ming-Li (1999) found that when CO2 pressure increases, so do the strength losses. These additional strength losses are due to the greater adsorptive potential and dissolution ability of super-critical CO2. In this way, super-critical CO2 is able to access more of the coal matrix than sub-critical CO2, which can cause more effects on the coal seam integrity (see Table 3).

While this CO2 adsorption-induced strength reduction and crack formation cause the injected CO2 to be back-migrated into the atmosphere, there is an additional concern related to the potential for fault instability located between the deposited CO2 and the surface, leading to potential damage to infrastructure. Therefore, a better understanding of coal mass behavior is essential for the safe implementation of CO2 sequestration at a field scale.
Although CO₂ sequestration is a promising method to reduce and control the greenhouse gas effect through the geological storage of anthropogenic CO₂, it still remains in the experimental stage, as many aspects need to be studied before being put into practice to avoid the risks associated with this process. Most of the possible coal seams for CO₂ sequestration are thin (0.5–5 m), contain many faults and are

**Table 3** Effect of CO₂ injection on coal seam strength during the CO₂ sequestration process.

<table>
<thead>
<tr>
<th>Effective factor</th>
<th>Key observation</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adsorbing gas</td>
<td><strong>CO₂</strong> (sub-critical) saturation decreases the strength of brown coal, while for <strong>N₂</strong>, the effect is the opposite. This is because <strong>N₂</strong> is capable of replacing the existing <strong>CO₂</strong> in the coal mass by reducing the partial pressure of the seam and consequently recovering the swelling areas to some extent (Kiyama et al., 2011).</td>
<td>Axial stress vs. Axial strain curves for different saturation mediums (Perera et al., 2011c)</td>
</tr>
<tr>
<td>Coal rank</td>
<td><strong>CO₂</strong> saturation causes up to 4.5 times higher strength reduction in bituminous coal compared to lignite as there is a greater surface area in high density coal. High rank coal seams located deep underground offer greater loci for CO₂ adsorption due to their well-developed cleat system causing more swelling than low rank coal (Ranjith &amp; Perera, 2012).</td>
<td>Comparison of UCS strength reduction in bituminous and lignite coal (Ranjith &amp; Perera, 2012)</td>
</tr>
<tr>
<td>CO₂ pressure</td>
<td>• There is a linearly increasing trend for strength reduction with increased injection pressure (Perera et al., 2013)</td>
<td>Gaseous and super-critical CO₂ saturation effect on coal strength (Perera et al., 2011c, 2013)</td>
</tr>
<tr>
<td>and phase</td>
<td>• The increasing injection pressure has a significant negative effect on cleat performance with greater adsorption-induced swelling (Perera et al., 2013)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• A greater strength reduction (approximately 40%) in super-critical <strong>CO₂</strong> compared to normal gaseous <strong>CO₂</strong> due to the greater adsorptive potential for super-critical <strong>CO₂</strong> (Perera et al., 2013)</td>
<td></td>
</tr>
</tbody>
</table>
much lower in permeability (0.001–0.005 Darcy) (Gale, 2004). Therefore, CO₂ adsorption-induced swelling in such seams may develop higher stresses on the top (overlying) and bottom (underlying) rock strata, which can create possible migration paths for injected CO₂ out of the coal mass through the faults generated.

6 COAL CO₂ SEQUESTRATION FIELD PROJECTS

The USA, Canada, Poland, China, Australia, Japan and some other countries are using ECBM recovery via CO₂ sequestration at a field scale. Table 4 summarizes some of the main field-scale CO₂ sequestration projects in the world. In addition, initial testing for CO₂ sequestration in China has confirmed a large resource potential for CO₂ sequestration. There are two potential settings for CO₂ storage within China’s carboniferous coal deposits: the northeast China coal region and the Ordos basin in north central China. Of these, the northeast China coal region is heavily industrialized, with numerous coal-fired power plants that could provide cheap CO₂ for injection. The Ordos basin in north central China has superior reservoir quality, with minimal fracturing and higher permeability, and the potential for CO₂ sequestration is around 660 million tons in this basin (Stevens et al., 1999). In 2002, China initiated field-scale CO₂ sequestration with the collaboration of Canada, and during the first three years, the project was planned to perform three micro pilot tests before the selection of a suitable location meeting the requirements for a full-scale pilot test (White et al., 2005). According to Wong et al. (2007), the first micro-pilot test at the south Qinshui basin, Shanxi Province, China was successful and the field data were well-matched using a tuned reservoir model. Further, a multi-well pilot project was designed and planned to proceed (Wong et al., 2007).

However, most of the current field-scale CO₂ sequestration projects have faced the common issue of reduction of CO₂ injection capacity within 6 months to two years after initiation; due to coal matrix swelling (refer to Table 4). Interestingly, this matrix swelling-created CO₂ injectibility reduction has sometimes been recovered by the reduced effective pressure closer to the CO₂ injection well, and as a result considerable CO₂ injection capacity enhancements have been recorded (Fujinaka et al., 2010; White et al., 2005). However, the combined influence has mostly had a negative influence on CO₂ sequestration and coal seam gas production. Therefore, various coal seam permeability enhancement techniques, including inert gas (N₂) injection and hydro fracturing, have been performed in the field.

Of these projects, the Ishikari basin and Fenn Big Valley basin projects have injected pure N₂ (Mavor et al., 2004; White et al., 2005; Fujinaka et al., 2010) and the Fenn Big valley basin and Southern Bowen basin have injected a mixture of N₂ and CO₂ (flue gas) (Reeves & O’Neill, 1989; Mavor et al., 2004; White et al., 2005; Syed et al., 2013) into the coal seam to recover the CO₂ adsorption-induced swelled areas in the coal matrix to some extent. Although injecting an inert gas like N₂ (Mavor et al., 2004; White et al., 2005; Fujinaka et al., 2010) or a mixture of CO₂ and N₂ (Reeves & O’Neill, 1989; Mavor et al., 2004; White et al., 2005) can increase coal seam permeability by a substantial amount, that increase is not sufficient for an economical CO₂ sequestration project. Therefore, more advanced approaches, such as hydro fracturing, have been required to enhance coal seam permeability to achieve an acceptable CO₂
### Table 4: Field-scale CO₂ sequestration projects around the world.

<table>
<thead>
<tr>
<th>CO₂ sequestration project</th>
<th>Details of well configuration</th>
<th>Details of gas injection</th>
<th>Remarks</th>
<th>Figures</th>
</tr>
</thead>
</table>
| **Allison unit San Juan basin – USA**  
(Clarkson & Bustin, 1997; Reeves, 2001, 2002a; Reeves, 2002b; Reeves et al., 2002; Reeves & Oudinot, 2005; White et al., 2005) | Has 4 CO₂ injection wells and 9, CH₄ production wells, drilled at 320-acre spacing | • CO₂ was injected at a maximum injection pressure of 1.7 MPa  
• Over 6 ½ years, 6.4 Bcf of CO₂ was injected | • The first experimental CO₂-ECBM recovery pilot project in the world, started in 1995 and the rank is medium to low volatile bituminous coal.  
• Initially, significant reduction in injectivity was observed due to coal matrix swelling and effective stress increment.  
• Gas production caused the overall reduction of pressure and reservoir volume and caused CO₂ adsorbed near the injection wells to be desorbed and migrate further from the wells. This increased permeability by reversing the swelling areas closer to injection wells. | ![Allison Unit- San Juan basin, USA (Reeves, 2001)](image1) |
| **Williston basin North Dakota – USA**  
(Botnen et al., 2009; Perera & Ranjith, 2012; White et al., 2005) | Consists of five wells to around 340m depth | • Estimated CO₂ storage capacity is 10.3 TCU  
• Weakly developed cleat system was the main challenge for the injection of CO₂ | • Second largest coal deposit in USA, consists of lignite coal deposit  
• 13 molecules of CO₂ can be sequestrated for each molecule of CH₄  
• Due to coal mass swelling, 10-fold reduction was observed in first year | ![Williston basin, North Dakota – USA (Peterson & Schmoker, 1995)](image2) |
**Fenn Big Valley basin Alberta – Canada**

(Mavor et al., 2004; Perera & Ranjith, 2012; White et al., 2005)

- Consists of two wells
- Both CO$_2$ and flue gas were injected
- In 1997, 12 tons of CO$_2$ was injected and after a short process of CH$_4$ production, around 15 tons of CO$_2$ was injected.
- Since the absolute permeability of the coal seam was very low (1 mD) during the pure CO$_2$ period, flue gas (13% CO$_2$, 87% N$_2$) was injected into the same injection wells in 2000.
- Pure N$_2$ was injected to enhance the CO$_2$ injection rate and the absolute permeability of the coal seam was increased up to around 13.8 mD.
- Since the absolute permeability was reduced (1 mD) after 9 days, a mixture of CO$_2$ and N$_2$ (47% CO$_2$, 53% N$_2$) was injected, which increased the absolute permeability up to 5.6 mD.

- Consists of 500 TCU out of 700 TCU coalbed methane resources in Canada
- First pilot test of injecting flue gas in the world
- Rank is high volatile B-bituminous

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Fenn Big Valley basin Alberta – Canada (Gentzis et al., 2008)
<table>
<thead>
<tr>
<th>CO₂ sequestration project</th>
<th>Details of well configuration</th>
<th>Details of gas injection</th>
<th>Remarks</th>
<th>Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dowson river site Southern Bowen basin Australia (Perera &amp; Ranjith, 2012; Reeves &amp; O’Neill, 1989)</td>
<td>Three major phases</td>
<td>During first phase CO₂ is injected followed by a soak period, to allow the CO₂ to be adsorbed into coal. During second phase, both pure CO₂ and a mixer of CO₂ and N₂ is injected.</td>
<td>Estimated CBM resource base is 178 Tscf. The coals are high-volatile bituminous A and B. The timing of the demonstration is 4.3 years. If the project were to be successful, phase 3 would become a commercial operation.</td>
<td>Bowen Basin Location of Southern Bowen basin, Australia (Source: Reeves &amp; O’Neill, 1989)</td>
</tr>
</tbody>
</table>
Silesian basin, Poland
(Reduction of CO$_2$ Emissions by Means of CO$_2$ Storage in the Silesian Coal Basin of Poland – RECOPL)
(Perera & Ranjith, 2012; Reeves & Taillefert, 2002; White et al., 2005)

One CO$_2$ injection well and one CH$_4$ production well located 105 m from each other

- During first 6 months (in 2004) of CO$_2$ injection, permeability was reduced from 10–100 (CO$_2$ injection capacity – 1 ton/day) from the initial permeability (CO$_2$ injection capacity – 20 ton/day)
- In mid-2005, a hydraulic fracture was created and CO$_2$ injection capacity increased up to 15 tons/day

- Small-scale project
- 93% of the injected CO$_2$ was stored and 55-70% enhancement of CH$_4$ production was observed from the field tests

Ishikari basin Yubari – Japan
(Fujioka et al., 2010; Perera & Ranjith, 2012; White et al., 2005)

Two CO$_2$ injection wells and one CH$_4$ production well

- During the first year, without any gas production, a total of around 35.7 metric tons of CO$_2$ was injected at a rate of 2.3 tons/day, which reduced to 11 metric tons in the second year
- Due to decrease of effective pressure closer to the injection well, CO$_2$ injection was increased from 1.6 tons/day to 3.5 tons/day
- The N$_2$ injection in 2005, enhanced the CO$_2$ injection up to 6.6 tons/day and gradually dropped again to the initial rate, and was then again increased because of effective stress variation.

- Small-scale project
- Injection pressure was maintained at 15 MPa, which was slightly less than the cleat opening pressure of 15.8 MPa
- A total of 480 tons of CO$_2$ was injected between 2004–2006

Location of Silesian basin, Poland (Reeves & Taillefert, 2002)

Location of Ishikari coal basin, Japan (Fujioka et al., 2010)
injection capacity in the field (Ruehl, 1968; Mazza et al., 1981; Puri et al., 1991; Reeves & Taillefert, 2002). Hydro fracturing techniques have already been tested in some field-scale projects, including the Silesian basin (Reeves & Taillefert, 2002; White et al., 2005). However, there are some disadvantages to the hydro fracturing process, since the creation of hydraulic fractures may cause the coal seam to be weakened, and this may enhance the risk of injected CO$_2$ back-migration into the atmosphere. Therefore, creating hydro-fractures in coal seams, where they have already been weakened due to super-critical CO$_2$ injection, becomes a greater challenge and no extensive study has been conducted regarding this matter to date. Therefore, a far-reaching study is required, using comprehensive experiments under laboratory conditions or advanced numerical modeling approaches, before putting hydro fracturing into practice.

7 WHAT CAUSES THE LACK OF CO$_2$ SEQUESTRATION IMPLEMENTATION?

Basically, CO$_2$ sequestration in deep coal seams can be divided into two general sub-systems: operational and in situ. The operational sub-system includes components such as CO$_2$ capture, transportation, and injection. Once CO$_2$ is injected into coal beds, it enters an in situ sub-system. The past technological innovations and experiences have provided the tools and proficiency to handle and control CO$_2$ in the operational sub-system with adequate certainty and safety; however, in the in-situ sub-system knowledge is currently lacking, particularly of the environmental and human health risks. Furthermore, public perceptions, the economics of CO$_2$ sequestration and policy barriers are other challenges which discourage the use of CO$_2$-ECBM projects in spite of their multiple advantages (Bae & Bhatia, 2006; Holloway, 2005; Howard, 2002).

7.1 Complexity associated with coal heterogeneity

Some characteristics are required for effective and safe CO$_2$ sequestration in coal seams. These include i) sufficient capacity for storing large volumes of CO$_2$, ii) adequate CO$_2$ injectivity (permeability of at least 1–5 mD), iii) a minimally faulted and/or folded reservoir, and iv) a reservoir well confined with an overlying seal to prevent leakage of injected CO$_2$ into the atmosphere (Bachu, 2007; Gale & Freund, 2001). However, the satisfaction of all of these criteria is challenging and is made complex by the highly heterogeneous nature of coal. As discussed in Sections 4 and 5, the behavior of CO$_2$ permeability and coal seam strength vary with the seam and injecting CO$_2$ properties (coal rank, temperature, confining pressure, CO$_2$ phase and pressure). This leads to unpredictable CO$_2$ injectivity and coal seam integrity. In addition, the heterogeneous nature of coal increases the uncertainty in determining the properties representative of a whole seam (Day et al., 2008; Ozdemir & Schroeder, 2009; Renzik et al., 1978; Robertson, 2005; Saghaﬁ et al., 2007; Wang, 2007). Furthermore, there may be significant variations in properties within the same core sample or between different
core samples obtained from the same coal seam. Therefore, the heterogeneous nature of coal has been a key hurdle to the confirmation of the effects of in situ coal properties on coal’s behavior.

According to De Silva & Ranjith (2013) and Jasinge et al. (2011), homogenous reconstituted coal samples with reproducible properties can be used to overcome this problem. Figure 9 shows the variation of permeability with effective stress for reconstituted and natural samples of brown coal. The figure depicts very similar permeability behavior of CO$_2$ in the natural specimen and the reconstituted specimen (Jasinge et al., 2011). Therefore, reconstituted coal samples can be used to avoid the complexities associated with coal heterogeneity. However, thorough investigation of the coal mass structure and its characteristics for different localities is crucial for the safe execution of CO$_2$-ECBM at a field scale.

### 7.2 Environmental and human health risks

The question of whether safe and stable storage of CO$_2$ in the sub-surface can be assured is probably the most important issue facing the underground storage of CO$_2$ at present, because this is likely to have a high impact on public acceptability. To protect the environment and the health and safety of the public, monitoring and verification of geologically-sequestered CO$_2$ is essential. Moreover, it is essential to satisfy the expected regulatory demands and to lessen any uncertainties associated with the long-term safety and the security of projects (White et al., 2005). In-situ pressure gauges, chemical tracers, isotropic ratios, geophysical methods, visual inspection and the production response by nearby wells are some methods used for the detection of movement of stored CO$_2$ (Hall et al., 1994). However, due to the limitations and uncertainties associated with those methods, it has become perplexed in fulfilling the monitoring process such as: (i) uncertainties that are due to wellbore storage effects in using pressure gauges, (ii) adsorptive nature of coal may irreversibly

![Figure 9 Permeability behavior with effective stress for natural and reconstituted coal samples (Jasinge et al., 2011).](image-url)
sorb the compounds added as chemical tracers, and (iii) precision of the measurements during geophysical methods (Chikatamarla et al., 2004; White et al., 2005).

7.3 Policy, regulation and public perceptions of CO$_2$ sequestration using ECBM

For the operation of CO$_2$ sequestration in a safe and secure manner, the formation and application of sound regulatory and legal frameworks are essential. Public perceptions, policies, regulations and international conventions exist which may offer assistance or barriers to CO$_2$ capture and storage using ECBM recovery.

7.3.1 Policies, regulations and international agreements

The use of CO$_2$ sequestration will add to the cost of fossil fuel energy with some exceptions. Worldwide disposition of CO$_2$ sequestration could be encouraged by policies that address the added cost of CO$_2$ storage, not only in developed countries but also in countries where access to affordable energy is a key development priority. Some national governments have provided limited early inducements for CO$_2$ sequestration projects, while the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol could both be used to encourage CO$_2$ storage. For example, the UNFCCC has accepted Norway’s national inventory of greenhouse gas emissions, under which CO$_2$ from the Sleipner gas field that has been geologically stored does not contribute to Norway’s emissions (Kheshgi et al., 2005). To date, no CO$_2$ sequestration projects have been submitted for approval under the Clean Development Mechanism of the Kyoto Protocol (Kheshgi et al., 2005). Within the European Union (EU) Emissions Trading System, CO$_2$ stored in geological formations can be deducted from Member States’ inventories, based on the provisional monitoring guidelines of Member States, until succeeded by permanent EU monitoring guidelines (Kheshgi et al., 2005). In the long term, the effective application of CO$_2$ storage will rely on economically efficient approaches to address the additional costs.

An effective legal and regulatory framework would facilitate good CO$_2$ sequestration practices without forming unintended barriers to the deployment of CO$_2$ sequestration. An expanded use of coal CO$_2$ sequestration would be accompanied by reductions in costs, improvements in technology, and improved understanding of risks and their management. A regulatory framework that encourages good practice and incorporates the evolving understanding of risk and its management could promote these improvements.

7.3.2 Public perception

Public acceptance and support is of great importance for coal CO$_2$ sequestration. At this stage the public is largely unaware of coal CO$_2$ sequestration. Early experience will leave a legacy for coal CO$_2$ sequestration in terms of public perceptions of it. Clear assessment of the merits of coal CO$_2$ sequestration and the competing technologies is a prerequisite for informed decisions. This would enable the merits of each option to be
weighed in the context of a broad range of priorities, including the long-term risks of climate change.

8 CONCLUSIONS AND SUGGESTIONS

8.1 Conclusions

- With the process of industrialization and modernization, carbon dioxide emission is becoming a major concern directly leading to global warming. Various approaches have been proposed to effectively address the problem by significantly reducing the amount of greenhouse gas (CO$_2$) in the atmosphere, including the use of renewable fuels, energy-efficient technology and carbon sequestration. Of these feasible methods, carbon dioxide sequestration in deep un-mineable coal seams is recognized as one of the most promising methods, for cost and safety considerations.

- CO$_2$ sequestration involves the capture of CO$_2$ released from anthropogenic sources and its secure storage in deep underground locations off-shore or on-shore. However, in terms of safety, reliability and cost, on-shore sequestration is more effective than off-shore sequestration. Of the various potential CO$_2$ storage sinks deep underground (e.g. depleted oil and gas fields, saline aquifers, shale beds, and coal mines), CO$_2$ storage in deep coal seams offers unique advantages, and the offsetting of CO$_2$ sequestration costs by the production of a valuable energy product like methane (coal seam gas) is critical. This process is known as enhanced coal bed methane (ECBM) recovery.

- However, adsorption of the injected CO$_2$ into the coal mass causes it to swell, leading to significant alterations in its internal rock mass structure, resulting in major modifications to CO$_2$ injectivity and coal mass integrity. This CO$_2$ adsorption-induced coal matrix swelling process is dependent on both seam (coal rank, temperature and confining pressure) and injected CO$_2$ properties (CO$_2$ phase and pressure), and the swelling reduces with increasing temperature due to the reduced sorption capacity. On the other hand, the amount of swelling is largely dependent on the pressure and the physical state of the injected CO$_2$, and super-critical CO$_2$ creates a much greater swelling effect than sub-critical CO$_2$, due to its higher chemical potential. Furthermore, high-pressure injection of CO$_2$ causes the swelling process to be enhanced due to the higher flow ability of the injected CO$_2$ under reduced effective stress conditions (difference of confining pressure and injection pressure) at increased injection pressures. However, potential coal seams for CO$_2$ sequestration process are available at extremely deep locations and there is a high possibility of phase change from sub- to super-critical state in the underground environment owing to changes in field conditions. This confirms the likely existence of high swelling rates in deep coal seams with CO$_2$ injection.

- The effectiveness of the CO$_2$ storage process in any coal seam is greatly influenced by the flow ability of the injected CO$_2$ through the seam, which is dependent on a number of factors, including coal rank, seam temperature, seam depth (confining pressure) and CO$_2$ injecting pressure and phase. Importantly, the injected CO$_2$ phase condition critically influences its flow behavior in the seam. In the super-critical state, the expected form of the CO$_2$ in deep coal seams, CO$_2$ has
significantly lower permeabilities than sub-critical CO₂, which causes unpredictable CO₂ injectibilities into deep coal seams.

- Secure storage of injected CO₂ in the seam is critically important in CO₂ geosequestration in deep coal seams in terms of environmental health and safety. It is important to prevent the back-migration of CO₂, as this has potential to cause mine outbursts and lateral migration into aquifers and surrounding more permeable geologic strata. These factors are mainly dependent on the coal mass strength properties. However, it is well known that CO₂ adsorption-induced swelling causes weakening in deep coal seams. This strength reduction is greatly dependent on injecting CO₂ phase and pressure, and it increases with increasing pressure. In addition, super-critical CO₂ creates much greater strength reduction than sub-critical CO₂. High rank coal seams located deep underground are subjected to greater strength reduction with CO₂ injection, as they offer greater loci for CO₂ adsorption.

- Reduction of seam permeability over time (after CO₂ injection) is a common issue faced by many field-scale CO₂ sequestration projects. For example, there was around 50% reduction in CO₂ injectivity at the Allison unit CO₂ sequestration project in the San Juan basin, USA, during the first two years of injection.

- Existing government policies, public perceptions, and strict rules on coal mining affect the implementation of CO₂ sequestration in deep coal seams. The lack of knowledge related to coal seam CO₂ sequestration has severely affected the implementation of this process in potential coal seams around the world. The complex heterogeneous nature of coal (which causes location-dependent coal seam properties) is the reason for the delay in, adoption of coal CO₂ sequestration.

8.2 Recommendations

- Extensive laboratory tests on different type of coals can be used to obtain a clearer view of the effects of CO₂ sequestration in coal mass in a controlled environment. These results can be used to support reservoir studies and then be extended to other advanced studies (risk assessment studies, economic optimization studies, project-screening models etc.).

- Numerous studies have been conducted on CO₂ sequestration in coal seams. However, knowledge regarding enhanced methane production remains limited. Therefore, more attention to enhanced methane production-related coal seam alterations is required.

- More demonstration projects of CO₂ storage in deep coal seams are required to increase knowledge of CO₂ sequestration-induced flow and mechanical property changes.

- A detailed monitoring system (near-surface monitoring and seam monitoring) is essential for the CO₂ sequestration projects to ensure the integrity of the CO₂ storage and CH₄ production process and to avoid the possible hazards related to CO₂ back-migration into the atmosphere. This would lead to higher confidence and improved public perceptions.
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