2019

Evaluation of Coal Seam Gas Drainability for Outburst-Prone and High-CO2-Containing Coal Seam

Lei Zhang  
*China University of Mining and Technology, lz811@uowmail.edu.au*

Ting X. Ren  
*University of Wollongong, tren@uow.edu.au*

Naj Aziz  
*University of Wollongong, naj@uow.edu.au*

Cun Zhang  
*China University of Mining and Technology*

Follow this and additional works at: [https://ro.uow.edu.au/eispapers1](https://ro.uow.edu.au/eispapers1)

Part of the Engineering Commons, and the Science and Technology Studies Commons

**Recommended Citation**  
Zhang, Lei; Ren, Ting X.; Aziz, Naj; and Zhang, Cun, "Evaluation of Coal Seam Gas Drainability for Outburst-Prone and High-CO2-Containing Coal Seam" (2019). *Faculty of Engineering and Information Sciences - Papers: Part B*. 2925.  
[https://ro.uow.edu.au/eispapers1/2925](https://ro.uow.edu.au/eispapers1/2925)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
Evaluation of Coal Seam Gas Drainability for Outburst-Prone and High-CO2-Containing Coal Seam

Abstract
This paper presents the results of an evaluation study of gas drainability in the Bulli seam in the Southern Coalfield of the Sydney Basin, NSW, Australia, where the coal seam gas (CSG) contains a high proportion of carbon dioxide (CO₂). Historically the gas drainability in some particular areas of this coal seam was found to be particularly poor, which posed a significant challenge to gas predrainage. As a result, a large volume of greenhouse gases were released to the atmosphere during mining of the coal seam. Furthermore, the high gas content associated with the CO₂-rich composition also increased the risks of coal and gas outburst incidents, affecting the safety of mining. After systematic literature review of evaluation factors affecting gas drainability, this evaluation study comprehensively analyzed the main critical factors, including the geology of the area, the coal cleat system, coal microstructure, coal permeability, coal sorption capacity, gas content, and gas composition. Field geology analysis showed geological variations that affected the variations of the coal cleat system and CO₂ content in the coal seam. Scanning Electron Microscope (SEM) tests showed the tight and less-porous features in hard-to-drain coal samples. The colliery gas database analysis was carried out to assess the impact of gas content and gas composition on the drainability of the coal seam. Laboratory tests showed that the coal seam had a permeability of less than 1 mD and also showed that the coal seam was highly undersaturated, especially with high CO₂ content.

Keywords
drainability, outburst-prone, evaluation, high-co2-containing, coal, seam, gas

Disciplines
Engineering | Science and Technology Studies

Publication Details
Zhang, L., Ren, T., Aziz, N. & Zhang, C. (2019). Evaluation of Coal Seam Gas Drainability for Outburst-Prone and High-CO2-Containing Coal Seam. Geofluids, 2019 3481834-1-3481834-14.

This journal article is available at Research Online: https://ro.uow.edu.au/eispapers1/2925
Research Article
Evaluation of Coal Seam Gas Drainability for Outburst-Prone and High-CO₂-Containing Coal Seam

Lei Zhang, Ting Ren, Naj Aziz, and Cun Zhang

1 Key Laboratory of Deep Coal Resource Mining (Ministry of Education of China), State Key Laboratory of Coal Resources and Safe Mining, School of Mines, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China
2 School of Civil, Mining & Environmental Engineering, Faculty of Engineering and Information Sciences, University of Wollongong, NSW 2522, Australia
3 School of Resource and Safety Engineering, State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), Beijing 100083, China

Correspondence should be addressed to Lei Zhang; leizhangcumt@163.com

Received 9 July 2018; Accepted 10 October 2018; Published 17 February 2019

Copyright © 2019 Lei Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper presents the results of an evaluation study of gas drainability in the Bulli seam in the Southern Coalfield of the Sydney Basin, NSW, Australia, where the coal seam gas (CSG) contains a high proportion of carbon dioxide (CO₂). Historically the gas drainability in some particular areas of this coal seam was found to be particularly poor, which posed a significant challenge to gas predrainage. As a result, a large volume of greenhouse gases were released to the atmosphere during mining of the coal seam. Furthermore, the high gas content associated with the CO₂-rich composition also increased the risks of coal and gas outburst incidents, affecting the safety of mining. After systematic literature review of evaluation factors affecting gas drainability, this evaluation study comprehensively analyzed the main critical factors, including the geology of the area, the coal cleat system, coal microstructure, coal permeability, coal sorption capacity, gas content, and gas composition.

Field geology analysis showed geological variations that affected the variations of the coal cleat system and CO₂ content in the coal seam. Scanning Electron Microscope (SEM) tests showed the tight and less-porous features in hard-to-drain coal samples. The colliery gas database analysis was carried out to assess the impact of gas content and gas composition on the drainability of the coal seam. Laboratory tests showed that the coal seam had a permeability of less than 1 mD and also showed that the coal seam was highly undersaturated, especially with high CO₂ content.

1. Introduction

Australia has the third largest coal reserves in the world, with 144.8 billion tonnes (Bt) of proved coal resources, including 68.3 Bt anthracite and bituminous coals and 76.5 Bt subbituminous and lignite coals [1]. The majority of Australia’s economic black coal resources exist in Queensland and New South Wales (Figure 1(a)), which jointly produce 96% of Australian black coal [2]. Open-cut mining accounts for approximately 75% of total saleable coal production, with the balance coming from underground mines. The condition where large volumes of CSG are entrained in the geological formations is common for coal seams in Australia, and mixed CO₂ and CH₄ CSG is often present. It is estimated that 40% of Australian longwall mines require regular gas drainage to manage coal seam gas emissions [3]. Due to the mixed CO₂/CH₄ gas, attention has been drawn to the impact on global climate change from coal seam gas emissions as coal production has powered Australian economic development [4]. Particularly in CO₂ outburst coal seams, it is a prerequisite to conduct gas predrainage to control emissions and ensure the safety of coal production.

Coal with extremely complex pore structure can store a large amount of CSG; CSG has also become an energy resource of global significance. In addition to USA, countries such as Canada, Australia, China, and India practice CSG drainage activities [5–10]. In Australia, the CSG drainage industry is growing rapidly and is becoming one of the
significant energy sources in both Queensland [6, 11] and New South Wales [5]. Thus, an evaluation study of the gas drainability of coal seams in the Sydney Basin was required to understand better the challenges of the low permeability, high geological stress, and various gas saturation degrees of this deposit in order to achieve efficient CSG recovery and capture.

Mining experience in Australia shows that CO₂ content can vary significantly within short distances in the same seam and within the same coal mine. Gas outbursts can occur at lower gas contents for CO₂ than for CH₄, and the presence of high CO₂ content in coal seams has been the cause of numerous gas outbursts during underground coal mining. During the last 50 years, many outbursts occurred in Australian mines. In some instances where the dominant gas is CO₂, outbursts happened more frequently. For instance, at Tahmoor, Metropolitan, and West Cliff collieries in the Illawarra coalfield in the southern part of the Sydney Basin, gas outbursts were caused mainly by CO₂. Due to the common occurrence of CO₂ in Australian coal seams and its implications for coal mining, the mechanism of CO₂ storage and flow in coal has been investigated during the last two decades [3, 5, 6].

Geological structure variations and the mechanism of the coal cleat system were considered in detail and have been found to be related to gas flow by many researchers [12–14], who have reported that gas drainage efficiency is affected by the porous microstructure and permeability of coal [6, 15–20].

Coal adsorption isotherms describe the maximum gas adsorption capacity of coal, which is one of the key characteristics that affect CSG drainage operations, outburst prevention, and CO₂ storage [5, 21–23]. Under certain conditions, different types of coal exhibit different sorption behavior with various gases [24–27]. Gas content and gas composition are some of the most important factors that affect coal mine operation and safety and are highly significant in CSG resource assessment and recovery operations [3, 22, 28, 29]. To prevent coal and gas outburst, the outburst threshold limit value (TLV), which stipulates the CSG limit for mining, has to be established for each mine. The capacity of the coal matrix to absorb gas as a function of pressure is described by the Langmuir sorption isotherm. Coals that are capable of holding the maximum amount of gas at a certain reservoir pressure and temperature condition generally are referred to as being “saturated” or, otherwise, “undersaturated.” The most successful CSG drainage and production occurs in coal seams that are close to fully saturated [15, 22]. Therefore, the degree of gas saturation in a coal has an important impact on gas drainage and production rates. A critical examination of the gas database from the Metropolitan Colliery also was carried out to evaluate the impact of gas content and gas composition on the drainability of the coal seam at this mine.

The Metropolitan Colliery, located at New South Wales (NSW) as shown in Figure 1(b), has exhibited problems in that the absorbed gas is hard to drain in some longwall blocks of the Bulli seam. Even with additional drainage boreholes, gas contents at some locations have not dropped below the
TLV within the available drainage lead time. The research was carried out, therefore, to identify the main factors contributing to drainage problems, establishing the fingerprints of coals that are able to give early warning of likely future drainage constraints. The present research program was a systematic study that included coal sorption capacity analyses and a fundamental study of sorption theory [23, 27, 30]. Coal permeability and gas enhancement studies [18, 31] had already been carried out and the relevant results published. In order to identify the main factors that would indicate that a deposit would be “hard-to-drain” and give early warning signs of the issue, the methodology for laboratory evaluation and investigation of CSG drainability and its influencing factors are described in the present paper.

2. Geological Background

The Bulli seam, which is being mined at the Metropolitan Colliery, is related to the Illawarra Coal Measures in the Sydney Basin. Faiz et al. [5] reported that the rank of Sydney Basin coal ranges from low to high volatile bituminous coal (vitrinite reflectance: 0.7–1.9%). The migration of gases mainly occurs upwards in an aqueous solution, following the pressure gradient. During the upward migration of gas-saturated solution, gas is released continually from the solution due to the decreasing pressure. Due to the lower solubility of CH$_4$ relative to CO$_2$, CH$_4$ is desorbed within the deeper strata, whereas increasing amounts of CO$_2$ are desorbed within the shallower strata. Therefore, in most parts of the Southern Coalfield, increasing volumes of CO$_2$ gas are observed at shallower depths.

A typical area of difficult drainage in the Metropolitan Colliery is shown in Figure 2. As shown from the geological survey, strike/slip faults and mylonite exist in typical hard-to-drain locations, i.e., the 8-11 cut through (c/t) of main gate (MG) 22. The mylonite is a fine-grained metamorphic rock, typically banded, resulting from the grinding or crushing of other rocks. It was reported that no stress-driven roof failures were observed in the MG 22 panel. The faulting intersecting MG 22 panel was characterized by vertical displacement (0.1 m), a mylonite band approximately 20–30 mm thick, slickensides, and jointing, parallel and subparallel to the main structure. The geological structures can influence coal seam permeability and CSG variation, and hence gas drainage. This faulting may become the source of cleat system variations, causing CO$_2$ and CH$_4$ variations in this area, and thus a possible high concentration of CO$_2$.

The coal proximate analysis information is shown in Table 1.

3. The Evaluation of Gas Drainability from the Coal Seam

Many factors may affect CSG extraction, and the two most important factors are the permeability and CSG saturation of the coal. CSG saturation determines the CSG reserves of the coal seam, and the ability of CSG to migrate depends on the permeability of the coal. Other factors, including adsorption and desorption ability, coal seam gas type, geological variations, fractures, and stresses, can affect the two major factors mentioned above and also affect indirectly the drainability of the CSG. Thus, the evaluation of CSG drainability from the coal seam focuses on the permeability of the coal seam and the coal seam gas saturation level.

For gassy and outburst risk coal seam [3, 5, 18], extremely low permeability is the main factor causing poor gas drainability, as shown in Table 2. The permeability of the poor gas drainability areas typically was less than 1 mD. However, due to the low economic benefit of CO$_2$-rich coal seams, the evaluation of CSG gas drainability from the coal targets mainly the CH$_4$ component. Because of the different seepage characteristics of CO$_2$ and CH$_4$, the CH$_4$ extraction evaluation index cannot be used to predict CO$_2$ extraction. However, other than the Sydney Basin described in this paper, other locations including China, Poland, and elsewhere have large CO$_2$ outburst coal seams [32]. If there is poor drainage before coal seam mining, a large volume of greenhouse gases can be released directly to the atmosphere during the process of coal seam mining. Due to the lack of an assessment standard for CO$_2$ drainability from coal seams, the extraction method is not ideal. An investigation of drainability evaluation methods was conducted during the present study, and the influencing factors were determined in the laboratory. It was carried out to find the reasons for poor drainability in CO$_2$ outburst coal seams and propose specific indicators to evaluate gas drainability from CO$_2$ outburst coal seams.

4. The Evaluation of Gas Drainability for Hard-to-Drain Areas

4.1. Cleat System Study: In general, coal can be characterized as a rock with a natural cleat network [12]. Cleating consists of two types: in one, the predominant cleat is called a face cleat, and in the other, it is a butt cleat, which often ends at intersections with face cleats [40]. King et al. [41] noted that the coal space accounts for less than 2 percent of the bulk seam volume, and the mechanism of gas storage is the same as in conventional reservoirs where the flow of gas is governed by Darcy’s law.

Figures 3 shows the cleat system in the Metropolitan lump coal samples. Typically, the coal bedding direction and the face and butt cleats can be clearly identified. It can be observed that this type of coal is “tight” with small cleat spacings and narrow apertures [12]. The Scanning Electron Microscope (SEM) micrographs that are presented later in this report show the cleat characteristics at higher magnification. Optimal gas production usually is achieved from coal seams that are characterized by highly fractured coal and wide aperture cleat networks, high cleat density, and intermediate cleat spacing [42–44].

To understand the cleat system, field visits were carried out to examine the coal seams and evaluate in situ stress conditions in relation to borehole drilling direction in the “hard-to-drain” area in the Metropolitan Colliery. Figure 4 shows the drainage borehole layout and the residual gas content after six months of drainage in a typical hard-to-drain area (the red points are the “Fail” drainage samples, while...
green points are the “Pass” drainage samples. The “Pass” or “Fail” classification was determined by the measured gas content and composition, as compared to the outburst threshold limit, which is given in Section 4.5.

As is shown in Figure 4, some boreholes are relatively more productive than are others drilled in different directions in the same area. By relating this field observation with the field-observed cleat system, some boreholes drilled perpendicular to the major cleat system (from drilling stub towards Mains or outbye) may be more productive, while boreholes drilled inbye are likely to be less effective for degassing. Regarding the mapped orientation of the major horizontal stress, it seems that the major stress direction is perpendicular to the major cleat direction, thereby sealing the major cleat and likely causing closure of boreholes that are orientated inbye. This also may contribute to the less effective gas drainage of the hard-to-drain areas.

Variations in the geological structure can influence both the coal seam cleat orientation and the permeability. Cleat orientation has been reported to be an important parameter for the permeability of coal. It is generally accepted, therefore, that boreholes drilled perpendicular to the face cleat tend to be more productive than boreholes drilled otherwise. Battino and Hargraves [46] reported that when testing in the Castor seam at Cook Colliery, using 21 m long, 43 mm diameter boreholes, the measured gas flow rates ranged from 85 to 175 L/min from boreholes drilled perpendicular to the major cleat. This was marginally higher than the flow rates from boreholes drilled parallel to the major cleat, which was up to 75 L/min.

Thus, geological variation, mineralization, and coal seam cleat system variations can influence gas drainage borehole arrangements and especially the optimal direction of the borehole for efficient gas drainage. Geological variations could be the source of cleat system variations, as well as permeability changes along different directions in the strata.

4.2. Coal Microstructure Study. It has been reported that gas drainage efficiency is related to the porous microstructure of coal [14, 17]. In order to better understand the CSG drainage production characteristics, information about the coal structure microstructure from the fracture and cleat system is required. Poor gas drainage of the coal seam can be caused by a tight and low porosity microstructure. The coal microstructures from both hard-to-drain and easy-to-drain areas were examined using SEM. The SEM results from coal samples taken from different drainability areas were obtained using a JSM-6490 LV instrument. SEM imaging technology can provide a reliable visual record of the microstructures of the coal. The secondary electron mode was adopted for the SEM investigations [47].

4.2.1. SEM Analysis of Hard-To-Drain Coal Samples. Coal samples collected from 9-10, 11-12 c/t in MG 22, in the hard-to-drain area of the Metropolitan Colliery were examined during the present study. The piece samples were prepared, including the surface directions perpendicular to and parallel with the coal bed. The samples were prepared with a thickness of 10 mm.

Zhang et al. [48] reported coal sample SEM images from hard-to-drain areas. It was observed that the dominating feature of these samples was that, in general, they exhibit a solid surface, which was observed both perpendicular to and parallel with the coal bed (Figure 5(a)). The coals belonged to the comparatively “tight” (i.e., relatively impermeable) coal type according to the microstructural analyses.

The SEM examinations of coal samples from the 11-12 c/t in MG 22 gave a pore size of ten microns parallel with the coal bed direction. Pores in the coal were found to be filled with mineral matter and coal particles (Figure 5(b)). In general, coals with a more porous structure and fewer mineral-filled pores have better gas flow characteristics. The porosity of a coal can be decreased when the macropores are filled with mineral matter, thereby reducing the...
Table 2: Summary table showing the evaluation factors that affect gas drainability.

| Coal samples location | Depth | Gas drainability | Gas type | Geological variation | Gas content | Gas adsorption capacity | Evaluation factor | Gas pressure | Permeability |
|-----------------------|-------|------------------|----------|----------------------|-------------|-------------------------|-------------------|--------------|--------------|
| Haishiwan Colliery, China [32] | 800 m | Poor | CH₄/CO₂ | Faults related | 0.3 to 10 m³/t (CO₂) 0.05 to 6.22 m³/t (CH₄) | V_Langmuir 33-26.69 m³/t (CO₂) | V_Langmuir 32.57–64.53 m³/t (CO₂) V_Langmuir 19.41–34.32 m³/t (CH₄) | 1.75 MPa | 0.00039–0.00051 mD |
| Southern Sydney Basin, Australia [5] | — | Poor | CH₄/CO₂ | Faults and folds related | 1-20 m³/t (CH₄ and CO₂) | V_Langmuir 32.57–64.53 m³/t (CO₂) | V_Langmuir 19.41–34.32 m³/t (CH₄) | — | — |
| Huainan Colliery, China [18] | 930 m | Poor | CH₄ | — | — | — | — | 3.7 MPa | 0.000146 mD |
| Luling Colliery, China [33] | 800 m | Poor | CH₄ | — | — | 8.08 m³/t (CH₄) | | — | — |
| Southern Qinshui Basin, China [34] | — | Poor | CH₄ | — | — | V_Langmuir 37.6 m³/t | V_Langmuir 38.66 m³/t | P_Langmuir 2.5 MPa | 5.1 MPa | 0.02 to 2 mD |
| Northern Appalachian Basin, USA [35] | — | Medium | CH₄ | Faults related | — | — | V_Langmuir 17.3 m³/t | P_Langmuir 2.25 MPa | 2.1 MPa | 10-30 mD |
| Black Warrior Basin, USA [36] | — | Medium | CH₄ | Multiple faults and fractures related | — | — | V_Langmuir 19.1 m³/t | P_Langmuir 2.861 MPa | 0.648 MPa | 10 mD |
| Rujigou Colliery, China [37] | 240 m | Poor | CH₄ | — | — | — | — | 0.56 MPa | 0.16 mD |
| Wulan Colliery, China [38] | 265 m | Poor | CH₄ | — | — | 12.74 m³/t (CH₄) | — | 1.3 MPa | 0.0074 mD |
| Songzao Colliery, China [39] | 200 m | Poor | CH₄ | Inclined, 22-35° | 19.96 m³/t (CH₄) | — | 1.12 MPa | 0.0009143 mD |
permeability of the coal. The mineral matter also can influence gas desorption and coal matrix shrinkage. Therefore, the cleats filled with minerals cause difficulties in drilling and gas drainage.

Additionally, according to the geological information, mylonite and intrusions were identified in the hard-to-drain areas. Microstructural examinations of the samples showed that it is possible for mylonite filling in microcleats to block the pores, with not much space left for gas flow, which results in low permeability and hard-to-drain coal. Intrusions, such as one of the geological anomalies, can result in the permeability in that region, and magmatic intrusions...
play an important role in the generation of CO₂ [49], which was confirmed by the high CO₂ concentration in the hard-to-drain areas.

4.2.2. SEM Analysis of Easy-to-Drain Coal Samples. The easy-to-drain coal samples were examined in the same conditions described previously, using the same apparatus that had been used to examine the hard-to-drain coal samples. In general, the pore structure of these two samples was easily observed in the SEM, as is shown in Figures 6 and 7. The microcleat openings and mineral matter of the microstructure play an important role in the productive gas drainage of coal seams.

The micron size pore system of coal from easy-to-drain areas was relatively prevalent parallel with the bed direction. Pores were observed from the 100 μm and 10 μm scales, and the images are shown in Figure 6. The size of pores in the 100 μm scale images was larger than 25 μm, and the size of pores in the 10 μm scale images was approximately 10 μm. The pore density shown in the 10 μm scale images was relatively higher than that of the 100 μm scale images. Compared to the sample shown in Figure 7, the sample from a hard-to-drain area seems to have less micron size pores than sample from easy-to-drain areas. Moreover, in easy-to-drain areas, the pores were mostly empty or were only partly mineralized, which means that coal seams in easy-to-drain areas have high permeability. This slide was similar to the features of the hard-to-drain area. Fracture structures also can be observed in this sample, as shown in Figure 7. In contrast to the fracture structures of a hard-to-drain area (Figure 5), the fracture structures of easy-to-drain areas were obviously well generated, and the fractures were mostly empty. Thus, a low-porosity structure and mylonite filling of the pore structure are factors that cause difficulty in gas drainage.

4.3. Coal Permeability Study. The permeability of a coal characterizes its capacity to transmit gas if there is a pressure or concentration gradient across it. The complex flow processes in porous media depend on the complexity of the microstructure of porous media [50], and permeability can vary significantly with stress condition [51–53], fluid pressure changes [42], and also according to gas type and gas pressure [54].

The primary methods of determining permeability include field measurement, laboratory experiments, and numerical simulations. A laboratory permeability test program was conducted in this study using two different permeability tests, which were carried out using two types of equipment. One type of permeability test was conducted...
along the radius of the coal sample using a multifunction outburst research rig (MFORR), which was reported previously [55]. The other type of permeability test was carried out along the axial direction of the coal sample and was carried out using a standard triaxial coal permeability cell [56, 57].

Zhang et al. [48] reported that, for hard-to-drain area coal samples, permeability starts to establish a stable level at less than 1 mD, with higher gas pressure, and under high-stress conditions, although permeability values appear different at lower gas pressures (Figure 8).

The permeability of coal has a significant influence on the entire process of gas drainage and CSG production in coal mines. Coalbeds are classified into four groups based on their in situ permeability (Table 3) [45]. It can be obtained from Table 3 that coalbed gas extraction can be carried out when the coal seam permeability is generally greater than 1 mD. However, for Australian coals, according to Figure 9, it indicates that Australian coal seams that are suitable for drainage (medium radius drill method) should have a gas content of more than 6 m³/t gas and a permeability greater than 2 mD at a depth of 150 to 500 m.

As the permeability test is carried out with N₂ gas and dry coal samples, the in situ permeability should be lower than the lab-tested permeability result. Due to the Metropolitan Colliery’s in situ conditions, the high rate of CO₂ and CH₄ mixture gas, and the presence of water in the coal matrix and boreholes, the in situ permeability may be less than 1 mD. Hence, with a coal seam depth of more than 400 m and a gas content of 7.76 m³/t in the typical hard-to-drain area, gas drainage in these areas will be poor if no enhancement techniques are employed.

4.4. Coal Sorption Capacity Study. The coal samples used in the ash content test were from the core samples after the fast desorption gas content test. Before the test, the coal samples were crushed to -212 μm and dried in a vacuum desiccator in an oven at 60°C. The ash content test of the coal followed the Australian Standard AS 1038.3-1989 [58].

The test results showed that the ash content of Metropolitan coal was around 12.53% (Aad), which can be regarded as a relatively low ash content coal. Generally speaking, low ash content coal has a larger gas adsorbing capacity than does high ash content coal, which also explains why this type of coal has a strong gas adsorbing capacity and therefore requires a longer drainage lead time to reduce the gas content below the threshold limit for safe mining operations.

The sorption of samples from the typical hard-to-drain area (from c/t 8-11 along MG 22) was tested (GME 2126, GME 2127, GME 2128, and GME 2130 sample test results are shown as the examples). The indirect gravimetric method was used to test the coal isotherm, and its test apparatus was shown in detail in previous studies [23, 27, 30]. All samples were prepared by crushing the sample to a powder size of -212 μm and then enclosing it in pressure bombs, which were charged separately with CO₂ and CH₄ at a temperature of 25°C. The first step used the helium expansion method to determine the volume of the void space in the bomb for each sample. Then, each of the bombs was charged with the test gas pressure.

| In situ permeability (K) | Drainability       |
|-------------------------|--------------------|
| K ≤ 1 mD                | No drainage        |
| 1 mD < K ≤ 5 mD         | Difficult drainage |
| 5 mD < K ≤ 9 mD         | Low drainage       |
| 9 mD < K ≤ 50 mD        | Successful drainage|

Table 3: Classification of coalbeds based on their permeability (after Ref. [45]).
gas. The level of charging gas pressure for the sorption test was carried out systematically at 1000 kPa and then 1500 kPa, 2000 kPa, 3000 kPa until 4000 kPa. Finally, the isotherms were obtained for the equilibrium pressure point and adsorbed gas volume. Figure 10 shows four representative test results from the hard-to-drain area, which exhibited a much higher sorption capacity with CO₂ than with CH₄.

4.5. Gas Content and Gas Composition Study. The gas content of the coal seam of the Illawarra Coal Measures varied from less than 1 to 20 m³/t. The gas composition of the CSG included CH₄, CO₂, N₂, C₂H₆, and other higher hydrocarbons [5]. The two main gases, CO₂ and CH₄, usually accounted for greater than 90% of the total CSG. Faiz et al. [59] reported that the majority of the CSG was generated in coal from the Jurassic and Early Cretaceous period. Faiz et al. [5] stated that, for the Illawarra Coal Measures, the CH₄ was mainly from magmatic sources, and the CO₂ was generated mainly in the Tertiary period.

The gas content tests with the rapid desorption method were conducted according to the Australian Standard AS3980:1999 [58], and the gas composition tests were conducted using a Varian CP4900 Four Channel Micro Gas Chromatograph (GC). In total, 519 core samples were collected from underground for testing. For each test sample, the following information was recorded from the analysis: core sample reference; outburst threshold limit value; measured total gas content Qₜ; gas content components including Q₄, Q₅, and Q₆ (m³/t); gas composition of desorbed gas including CH₄, CO₂, and CH₄/(CH₄ + CO₂) (%).

The outburst threshold limit has to be established to prevent outburst fatalities. The outburst threshold limit value (TLV) varies linearly and is related to the gas composition, increasing from a minimum in the condition of pure CO₂ to a maximum in the condition of pure CH₄. Many Australian underground coal mines are mining in areas that require the use of gas drainage to reduce coal seam gas content to below a prescribed threshold limit value (TLV). Factors contributing to poor drainage problem may include high coal rank and in situ conditions resulting in high sorption capacity, low gas content, high CO₂ gas composition, and high in situ gas pressure causing low coal saturation as well as coal microstructure and permeability affecting gas transport. In various parts of the Bulli seam of the Sydney Basin, the main seam gas is more of CO₂ than CH₄, thus high CO₂ and mixed gas CH₄ and CO₂ have been found in a number of locations in Tahmoor, Metropolitan, Appin, and West Cliff mines [3, 22, 45]. In these gassy outburst-prone coal mines, mine operators use intensive gas drainage drilling programs to collect coal cores for gas content testing, identify structures ahead of the mine workings, and deal with the increasing problems of gas drainage and drain gas to below the applicable TLV to ensure safe mining operations.

According to the test results, the whole database of the Metropolitan Colliery, containing 519 sample results, was studied. From the mine level values in the database, the threshold limits were generated. As shown in Figure 11, the gas content was 6.0 m³/t for pure CO₂ and 9.5 m³/t for pure CH₄. Thus, if the test gas content for a coal sample was under the TLV limit, the sample was marked as a “Pass”, otherwise, it was marked as a “Fail”.

Figure 11 shows the scatter distribution of the whole gas database and the database for a typical hard-to-drain area (8-11 c/t, MG 22). As shown in Figure 11(a), the scatter of the whole gas database for the 519 samples ranged from CO₂ rich to CH₄ rich. As shown in Figure 11(b), unlike the scatter for the whole gas database, the scatter for a typical hard-to-drain area (94 samples) was concentrated almost entirely in the CO₂-rich area, with the highest CH₄/(CH₄ + CO₂) ratio being 0.21. Both of the results indicate that the seam is in a CO₂-rich condition, and in the typical hard-to-drain area, there is an especially high CO₂ condition.

In the zone where the CH₄/(CH₄ + CO₂) ratio was less than 0.2, 171 samples were designated as a “Fail”, which accounted for 88.1% of the total number of “Fail” samples. Including the “Pass” samples, 41.0% of samples in the zone with a CH₄/(CH₄ + CO₂) ratio of less than 0.2 were failed, compared to 22.5% of samples in the zone with a CH₄/(CH₄ + CO₂) ratio of more than 0.2. Comparing these results, in the zone with a CH₄/(CH₄ + CO₂) ratio of less than 0.2, 60 samples were designated a “Fail”, which accounted for 93.8% of the total number of “Fail” samples. Including the “Pass” samples, 65.9% of samples in the zone with a CH₄/(CH₄ + CO₂) ratio of less than 0.2 were failed. Both of
Figure 10: Coal adsorption isotherms at 25°C (a, b, c, and d are from typical hard-to-drain areas) (Ref. [45]).

Figure 11: Bulli seam outburst threshold limits. (a) Whole database. (b) Typical hard-to-drain area.
these results indicate that coal samples with a higher CO₂ composition condition were more prone to “Fail”.

Table 4 shows the test results for the whole gas database and for the database of a typical hard-to-drain area. The accounting ratio for the “Fail” samples was much higher at 67.0% in the typical “hard-to-drain” area, whereas the ratio for the whole mining area was 37.4%. The difference in the average Qₐ value between the “Pass” and “Fail” samples was smaller in the typical “hard-to-drain” area than for the whole mining area. The average CO₂ composition value was higher for both types of samples in the typical hard-to-drain area, whereas the ratio was even higher in the typical “hard-to-drain” area than for the whole mining area. This phenomenon also confirmed that in the sample tests with higher gas contents, the gas was more prone to release during the Q₁ testing processes.

The CO₂ isotherm, compared to CH₄ isotherm, has a more significant role in the gas drainage behavior for the researched coal seam. The critical desorption point of a typical Bulli seam sample is based on isotherms representing the adsorption capacity for both pure CH₄ and CO₂. Considering the same initial in situ gas content and pressure, it can be concluded that a CO₂-rich coal requires a far larger reduction in reservoir pressure to reach the critical desorption point than does an equivalent CH₄-rich sample [3]. All the above information demonstrate the important factors that characterize why it is more difficult to drain gas from the CO₂-rich Bulli seam gas than from the normal CH₄-rich coal seams, and why the typical “hard-to-drain” area is especially hard-to-drain when it has an even higher CO₂ gas composition.

5. Conclusions

An investigation of the drainability evaluation of outburst-prone and high-CO₂-containing coal seam, and its influencing factors, was carried out. In this study, coal cleat systems were investigated both in the laboratory and the field. The geological variations cause differences in coal permeability and CO₂ concentration. The SEM analysis showed that tighter and lower porosity microstructures were found for coals from the “hard-to-drain” areas than was the case for “easy-to-drain” areas.

Both the axial and radial permeability test results showed that the permeability of the coal decreased with an increase in stress and gas pressure. The permeability test results established a stable level of less than 1 mD under higher gas pressure and higher stress, which could be another possible reason that may explain the “hard-to-drain” behavior.

Compared to the CH₄ isotherm, the CO₂ isotherm of higher sorption value should have a greater significance in the gas drainage behavior of the researched coal seam. The researched coal seam, which had a higher CO₂ gas adsorption capacity and concentration, had a low gas saturation limit, which explained the “hard-to-drain” problem.

The results of the critical gas content and composition investigation were applied to the whole colliery gas database and to the hard-to-drain database. It was established that coal samples from CO₂-rich areas had a higher risk of failure, especially in the case of typical hard-to-drain areas.

A direct warning index for the in situ “hard-to-drain” problem was proposed as guidance for future gas drainage operations at the colliery, including areas with relatively

---

**Table 4:** Test results of the whole gas database and typical hard-to-drain area database.

| Categories                      | Whole gas database | Typical hard-to-drain area database |
|---------------------------------|--------------------|-------------------------------------|
|                                 | “Pass” samples     | “Fail” samples                      | “Pass” samples     | “Fail” samples     |
| Number of samples               | 325                | 194                                 | 31                  | 63                  |
| Accounting ratio                | 62.6%              | 37.4%                               | 33.0%               | 67.0%               |
| Average Qₐ value                | 4.4 m³/t           | 9.2 m³/t                            | 5.2 m³/t            | 7.8 m³/t            |
| Average CH₄ composition value   | 17.1%              | 14.0%                               | 8.5%                | 12.5%               |
| Average CO₂ composition value   | 73.5%              | 82.6%                               | 4.6%                | 4.5%                |
| Accounting ratio                |                    |                                     |                     |                     |

**Table 5:** The individual content of each gas component and the total gas content of each sample.

| Classification | Average Q₁ gas content (m³/t) | Average Q₁ : Qₐ ratio (%) | Average Q₂ gas content (m³/t) | Average Q₂ : Qₐ ratio (%) | Average Q₃ gas content (m³/t) | Average Q₃ : Qₐ ratio (%) |
|----------------|-------------------------------|---------------------------|-------------------------------|---------------------------|-------------------------------|---------------------------|
| All samples    | 0.5                           | 6.0                       | 1.2                           | 17.1                      | 4.5                           | 76.9                      |
| “Pass” samples | 0.2                           | 4.0                       | 0.6                           | 14.1                      | 3.6                           | 81.9                      |
| “Fail” samples| 1.0                           | 9.5                       | 2.2                           | 22.0                      | 6.0                           | 68.5                      |

---
lower gas contents (6-10 m³/t), areas with high CO₂ compositions (CO₂ > 80%, CH₄ < 20% or CH₄/(CH₄ + CO₂) < 0.2), and areas with geological variations.

In conclusion, a high gas storage capacity, relatively low gas contents, and a high CO₂ concentration result in low gas saturation limit for a coal. Geological variations and geostresses affect the coal microstructure, geological variations, and gas storage capacity, and a low porosity structure will cause low permeability in the coal. A low gas saturation limit and low permeability directly cause the coal to be hard to drain for CSG. Additionally, indirect factors that cause the difficulty in gas draining, such as high CO₂ concentration, geological variations, and geostresses, also influence each other and result in low permeability in the coal. The difficulty in gas draining and outburst risk are caused by a combination of these factors, especially when most of the features appear within a particular coal seam area.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments
This research is supported by the Fundamental Research Funds for the Central Universities (2017XKZD06) and the Priority Academic Programme Development of Higher Education Institutions in Jiangsu Province. The authors wish to thank the staff and management of Metropolitan Colliery for providing coal samples and related data used in this study. Thanks are also due to the technical staff at the University of Wollongong especially Col Devenish for experiment assistance.

References
[1] Statistical Review of World Energy (SRWE), 2017, https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf.
[2] Australian Bureau of Agriculture and Resource Economics (ABARE), 2010, http://www.doc88.com/p-9942184586705.html.
[3] D. Black and N. Aziz, “Impact of coal properties and operational factors on mine gas drainage,” in 10th Underground Coal Operators’ Conference, University of Wollongong, pp. 229–240, NSW, Australia, 2010, https://ro.uow.edu.au/coal/323/.
[4] Y. P. Cheng, L. Wang, and X. L. Zhang, “Environmental impact of coal mine methane emissions and responding strategies in China,” International Journal of Greenhouse Gas Control, vol. 5, no. 1, pp. 157–166, 2011.
[5] M. M. Faiz, A. Saghafi, S. A. Barclay et al., “Evaluating geological sequestration of CO₂ in bituminous coals: the southern Sydney Basin, Australia as a natural analogue,” International Journal of Greenhouse Gas Control, vol. 1, no. 2, pp. 223–235, 2007.
[6] E. C. P. Kinnon, S. D. Golding, C. J. Boreham, K. A. Baublys, and J. S. Esterle, “Stable isotope and water quality analysis of coal bed methane production waters and gases from the Bowen Basin, Australia,” International Journal of Coal Geology, vol. 82, no. 3-4, pp. 219–231, 2010.
[7] S. Hu, A. Zhang, G. Feng et al., “Methane extraction from abandoned mines by surface vertical wells: a case study in China,” GeoFluids, vol. 2018, Article ID 8043157, 9 pages, 2018.
[8] S. Sang, H. Xu, L. Fang, G. Li, and H. Huang, “Stress relief coalbed methane drainage by surface vertical wells in China,” International Journal of Coal Geology, vol. 82, no. 3-4, pp. 196–203, 2010.
[9] J. Cai, X. Hu, D. C. Standnes, and L. You, “An analytical model for spontaneous imbibition in fractal porous media including gravity,” Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 414, pp. 228–233, 2012.
[10] N. Zhang, F. Zhao, P. Guo et al., “Nanoscale pore structure characterization and permeability of mudrocks and fine-grained sandstones in coal reservoirs by scanning electron microscopy, mercury intrusion porosimetry, and low-field nuclear magnetic resonance,” GeoFluids, vol. 2018, Article ID 2905141, 20 pages, 2018.
[11] P. E. Hardisty, T. S. Clark, and R. G. Hynes, “Life cycle greenhouse gas emissions from electricity generation: a comparative analysis of Australian energy sources,” Energies, vol. 5, no. 4, pp. 872–897, 2012.
[12] S. E. Laubach, R. A. Marrett, J. E. Olson, and A. R. Scott, “Characteristics and origins of coal cleat: a review,” International Journal of Coal Geology, vol. 35, no. 1-4, pp. 175–207, 1998.
[13] X. Su, Y. Feng, J. Chen, and J. Pan, “The characteristics and origins of cleat in coal from Western North China,” International Journal of Coal Geology, vol. 47, no. 1, pp. 51–62, 2001.
[14] J. Liu, Z. Chen, D. Elsworth, H. Qu, and D. Chen, “Interactions of multiple processes during CBM extraction: a critical review,” International Journal of Coal Geology, vol. 87, no. 3-4, pp. 175–189, 2011.
[15] R. A. Lamarre, “Downhole geomechanical analysis of critical desorption pressure and gas content for carbonaceous reservoirs,” in SPE Annual Technical Workshop on Coalbed Methane, Society of Petroleum Engineers, Durango, CO, USA, March 2007https://www.onepetro.org/general/SPE-110911-MS.
[16] Z. Pan, L. D. Connell, and M. Camilleri, “Laboratory characterisation of coal reservoir permeability for primary and enhanced coalbed methane recovery,” International Journal of Coal Geology, vol. 82, no. 3-4, pp. 252–261, 2010.
[17] T. A. Moore, “Coalbed methane: a review,” International Journal of Coal Geology, vol. 101, no. 6, pp. 36–81, 2012.
[18] L. Zhang, N. Aziz, T. Ren, J. Nemcik, and S. Tu, “Nitrogen injection to flush coal seam gas out of coal: an experimental study,” Archives of Mining Sciences, vol. 60, no. 4, pp. 1013–1028, 2015.
[19] J. Li, S. Lu, Y. Cai, H. Xue, and J. Cai, “Impact of coal ranks on dynamic gas flow: an experimental investigation,” Fuel, vol. 194, pp. 17–26, 2017.
[20] C. Zhang, S. Tu, and L. Zhang, “Analysis of broken coal permeability evolution under cyclic loading and unloading conditions by the model based on the hertz contact deformation
principle," *Transport in Porous Media*, vol. 119, no. 3, pp. 739–754, 2017.

[21] A. Saghafl, "Potential for ECBM and CO₂ storage in mixed gas Australian coals," *International Journal of Coal Geology*, vol. 82, no. 3-4, pp. 240–251, 2010.

[22] D. J. Black, "Factors affecting the drainage of gas from coal and methods to improve drainage effectiveness," *Sports Biomechanics*, vol. 13, no. 2, pp. 123–134, 2011, https://ro.uow.edu.au/theses/3339/.

[23] L. Zhang, T. Ren, and N. Aziz, "Influences of temperature and moisture on coal sorption characteristics of a bituminous coal from the Sydney Basin, Australia," *International Journal of Oil, Gas and Coal Technology*, vol. 8, no. 1, pp. 62–78, 2014.

[24] A. Saghafl, M. Faiz, and D. Roberts, "CO₂ storage and gas diffusivity properties of coals from Sydney Basin, Australia," *International Journal of Coal Geology*, vol. 70, no. 1–3, pp. 240–254, 2007.

[25] S. Day, R. Sakurovs, and S. Weir, "Supercritical gas sorption on moist coals," *International Journal of Coal Geology*, vol. 74, no. 3-4, pp. 203–214, 2008.

[26] A. Busch and Y. Gensterblum, "CBM and CO₂-ECBM related sorption processes in coal: a review," *International Journal of Coal Geology*, vol. 87, no. 2, pp. 49–71, 2011.

[27] L. Zhang, T. Ren, and N. Aziz, "Coal sorption characteristics and coal surface tension," *International Journal of Oil, Gas and Coal Technology*, vol. 8, no. 3, pp. 336–352, 2014.

[28] C. O. Karacan and E. Okandan, "Adsorption and gas transport in coal microstructure: investigation and estimation by qualitative X-ray CT imaging," *Fuel*, vol. 80, no. 4, pp. 509–520, 2001.

[29] L. Zhang, Z. Ye, M. Li, C. Zhang, Q. Bai, and C. Wang, "The binary gas sorption in the bituminous coal of the Huaibei Coalfield in China," *Adsorption Science & Technology*, vol. 36, no. 9-10, pp. 1612–1628, 2018.

[30] L. Zhang, N. Aziz, T. Ren, J. Nemcik, and S. Tu, "Influence of coal particle size on coal adsorption and desorption characteristics," *Archives of Mining Sciences*, vol. 59, no. 3, pp. 807–820, 2014.

[31] L. Zhang, C. Zhang, S. Tu, H. Tu, and C. Wang, "A study of directional permeability and gas injection to flush coal seam gas testing apparatus and method," *Transport in Porous Media*, vol. 111, no. 3, pp. 573–589, 2016.

[32] W. Li, Y. P. Cheng, L. Wang, H. X. Zhou, H. F. Wang, and L. G. Wang, "Evaluating the security of geological coalbed sequestration potential in China as a natural analogue," *International Journal of Greenhouse Gas Control*, vol. 13, no. 2, pp. 102–111, 2013.

[33] H. Zhou, R. Zhang, Y. Cheng, H. Dai, C. Ge, and J. Chen, "Methane and coal exploitation strategy of high-potential coal seams in the Huaibei Coalfield, China," *Forest Science*, vol. 50, no. 3, pp. 240–251, 2014.

[34] J. Luo, Y. Yang, and Y. Chen, "Optimizing the drilled well patterns for CBM recovery via numerical simulations and data envelopment analysis," *International Journal of Mining Science and Technology*, vol. 22, no. 4, pp. 503–507, 2012.

[35] C. O. Karacan, J. P. Uelry, and G. V. R. Goodman, "A numerical evaluation on the effects of impermeable faults on degasification efficiency and methane emissions during underground coal mining," *International Journal of Coal Geology*, vol. 75, no. 4, pp. 195–203, 2008.

[36] C. Ö. Karacan, "Analysis of gob gas venthole production performances for strata gas control in longwall mining," *International Journal of Rock Mechanics and Mining Sciences*, vol. 79, no. 9–18, pp. 9–18, 2015.

[37] T. Lu, H. Yu, T. Zhou, J. Mao, and B. Guo, "Improvement of methane drainage in high gassy coal seam using waterjet technique," *International Journal of Coal Geology*, vol. 79, no. 1-2, pp. 40–48, 2009.

[38] Y. Xue, F. Gao, Y. Gao et al., "Quantitative evaluation of stress-relief and permeability-increasing effects of overlying coal seams for coal mine methane drainage in Wulan coal mine," *Journal of Natural Gas Science and Engineering*, vol. 32, pp. 122–137, 2016.

[39] Y. Liu, "Technology of improving coal-seam permeability with high pressure pulsed water jet and its application on rock cross-cut coal uncovering," PhD Thesis, University of Chongqing, 2009.

[40] X. Cui, R. M. Bustin, and G. Dipple, "Differential transport of CO₂ and CH₄ in coalbed aquifers: implications for coalbed gas distribution and composition," *AAPG Bulletin*, vol. 88, no. 8, pp. 1185–1189, 2001.

[41] G. R. King, T. Ertekin, and F. C. Schwerer, "Numerical simulation of the transient behavior of coal-seam degassing wells," *SPE Formation Evaluation*, vol. 1, no. 2, pp. 165–183, 1996.

[42] X. Cui and R. M. Bustin, "Controls of coal fabric on coalbed gas production and compositional shift in both field production and canister desorption test," *SPE Journal*, vol. 11, no. 1, pp. 111–119, 2006.

[43] W. Solano-Acosta, M. Mastalerz, and A. Schimmelmann, "Geotechnical and geologic lineaments and coalbed methane potential in Pennsylvania coals in Indiana," *International Journal of Coal Geology*, vol. 72, no. 3-4, pp. 187–208, 2007.

[44] C. O. Karacan, F. A. Ruiz, M. Coté, and S. Phipps, "Coal mine methane: a review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction," *International Journal of Coal Geology*, vol. 86, no. 2–3, pp. 121–156, 2011.

[45] L. Zhang, "Study of coal sorption characteristics and gas drainage in hard-to-drain seams," PhD Thesis, University of Wollongong, NSW, Australia, 2013.

[46] S. Battino and A. J. Hargraves, *Seam Gas Drainage Experiments in Some Collies of BHP Seam Gas Drainage with Particular Reference to the Working Seam*, University Of Wollongong, Wollongong, Australia, 1982, https://www.osti.gov/etdweb/biblio/6649100/.

[47] B. Nie, X. Liu, L. Yang, J. Meng, and X. Li, "Pore structure characterization of different rank coals using gas adsorption and scanning electron microscopy," *Fuel*, vol. 158, pp. 908–917, 2015.

[48] L. Zhang, T. Ren, N. Aziz, and S. Tu, "Triaxial permeability testing and microstructure study of hard-to-drain coal from the Sydney Basin, Australia," *International Journal of Oil Gas and Coal Technology*, vol. 8, no. 4, pp. 432–448, 2014.

[49] J. L. Clayton, "Geochemistry of coalbed gas – a review," *International Journal of Coal Geology*, vol. 35, no. 1-4, pp. 159–173, 1998.

[50] J. Cai, B. Yu, M. Zou, and M. Mei, "Fractal analysis of invasion depth of extraneous fluids in porous media," *Chemical Engineering Science*, vol. 65, no. 18, pp. 5178–5186, 2010.
[51] J. Q. Shi and S. Durucan, “Modelling laboratory horizontal stress and coal permeability data using S&D permeability model,” *International Journal of Coal Geology*, vol. 131, pp. 172–176, 2014.

[52] G. Yin, C. Jiang, J. G. Wang, and J. Xu, “Geo-mechanical and flow properties of coal from loading axial stress and unloading confining pressure tests,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 76, pp. 155–161, 2015.

[53] C. Zhang, S. Tu, L. Zhang, Q. Bai, Y. Yuan, and F. Wang, “A methodology for determining the evolution law of gob permeability and its distributions in longwall coal mines,” *Journal of Geophysics and Engineering*, vol. 13, no. 2, pp. 181–193, 2016.

[54] Y. Gensterblum, A. Ghanizadeh, and B. M. Krooss, “Gas permeability measurements on Australian subbituminous coals: fluid dynamic and poroelastic aspects,” *Journal of Natural Gas Science and Engineering*, vol. 19, pp. 202–214, 2014.

[55] N. I. Aziz and W. Ming-Li, “The effect of sorbed gas on the strength of coal – an experimental study,” *Geotechnical & Geological Engineering*, vol. 17, no. 3/4, pp. 387–402, 1999.

[56] D. Jasinge, P. G. Ranjith, and S. K. Choi, “Effects of effective stress changes on permeability of Latrobe Valley brown coal,” *Fuel*, vol. 90, no. 3, pp. 1292–1300, 2011.

[57] M. S. A. Perera, P. G. Ranjith, S. K. Choi, and D. Airey, “The effects of sub-critical and super-critical carbon dioxide adsorption-induced coal matrix swelling on the permeability of naturally fractured black coal,” *Energy*, vol. 36, no. 11, pp. 6442–6450, 2011.

[58] Australian Standard, “Guide to the determination of gas content of coal-direct desorption method, AS 3980-1999,” 1999, https://www.standards.org.au/standards-catalogue/sa-snz/mining/mn-001/as–3980-1999.

[59] M. Faiz, L. Stalker, N. Sherwood et al., “Bio-enhancement of coal bed methane resources in the southern Sydney Basin,” *The APPEA Journal*, vol. 43, no. 1, p. 595, 2003.
