Coal Operators' Conference

Faculty of Engineering and Information Sciences

2012

Permeability testing of coal under different triaxial conditions

Lei Zhang
University of Wollongong

N. Aziz
University of Wollongong, naj@uow.edu.au

Ting Ren
University of Wollongong

Jan Nemcik
University of Wollongong

Zhongwei Wang
University of Wollongong

PERMEABILITY TESTING OF COAL UNDER DIFFERENT TRIAXIAL CONDITIONS

Lei Zhang , Naj Aziz, Ting Ren, Jan Nemcik and Zhongwei Wang

ABSTRACT: Permeability refers to the ability of coal to transmit gas when a pressure or concentration gradient exists across it.   The permeability of coal is dependent upon factors that include effective stress, gas pressure, water content, disturbance associated with drilling and matrix swelling/shrinkage due to adsorption/desorption.   A programme of laboratory tests were conducted on coal samples from the Bulli seam for evaluating the permeability and drainability of coal.   The study was conducted using two different types of permeability apparatus.   The methods of permeability testing of coal under different triaxial conditions are discussed.   Permeability testing of the Bulli seam coal sample with N_2 is described as an example in this study.   Both the tests results and the values of calculated permeability were in agreement.

INTRODUCTION

Permeability is considered by many researchers to have a significant impact on a coal seam's ability to produce gas (Jones, *et al.*, 1982; Osisanya and Schaffitzel, 1996; Zutshi and Harpalani, 2005 and Lamarre, 2007).   Permeability, which is closely related to the coal fabric (i.e. cleat spacing and aperture width), varies significantly as fluid pressure changes during coal seam gas production (Cui and Busten, 2006).   Permeability has a strong effect on the gas production profile and gas well performance.

Permeability measurements results, tested in small coal samples in laboratory conditions, have been shown to be different from *in situ* measured values.   Testing at Leichhardt Colliery, Gray (1982) found that, the measured core sample permeability was less than 5 mD, whereas the bulk permeability was found to be in the order of 200 mD, for drainage along the cleat.   This clearly indicates that more research is needed to focus on the accuracy of different measuring methods and the relationship between the laboratory permeability results and *in situ* coal permeability result.

A number of different permeability testing apparatus have been reported.   They are basically triaxial cells, which simulate the *in situ* conditions.   Some apparatus consists of a conventional triaxial cell, modified to provide gas inlet and exist ports through the upper and lower platens, Harpalani and Schraufnagel (1990), while others are more elaborate in design, such as those reported by Lingard *et al.* (1984), Lama (1995), Gillies *et al.* (1995) and Nakahima *et al.* (1995).   The mode of permeability testing, using these different apparatus however, can vary with respect to the way and role of the confinement pressure application.

Increased difficulty of seam gas drai**n**age occurs in sections of some coal seams such as the Bulli seam, which is due mainly to the changes in the permeability of the coal.   Such difficult to drain sections of the coal seam are generally associated with an increased percentage of the carbon dioxide.   Often reliance is made on the determination of the sorption isotherms rather than assessing the permeability of the coal for effective management of the seam gas drainage.   Reliance on sorption isotherms is understandable as it is much simpler method of estimating the gas content, and often decisions are made for gas drainage based on the gas content of coal.   A recent study by Black (2012) examining factors contributing to effective drainage of gas from coal found significant lack of information or insufficient level of data on coal permeability in comparison to other parameters such as gas content estimation and proximate analysis values.   Black's study was based on studies of data collected from more than 10 mines in Australia.   Difficulties associated with permeability determination in the laboratory or in the field experimentation, are mainly due to the fact both the laboratory and field tests raise concerns about the test method.   The laboratory tests are generally carried out on competent core samples, not truly representative of the real *in situ* condition, while field tests, though yielding representative results, intrude on a mine's operation and production.

In order to obtain representative permeability values with respect to effective gas drainage from the difficult to drain zone and permit a better understanding of the potential gas recovery through nitrogen injection and displacement process, a laboratory permeability testing programme was initiated by the gas research group of the University of Wollongong.   The programme consisted of duplicate testing of coal using two different permeability testing apparatus.   Both tests were carried out under triaxial test conditions. The first permeability testing method used is known as Multi Function Outburst Research Rig (MFORR) which was previously reported by Lama (1995), Aziz and Li (1999) and Farhang (2005), In this test, the sample was enclosed in a triaxial gas chamber.   The coal sample was subjected directly to gas as the confining pressure.   The pressured gas was made to filter through the coal sample while it is being loaded axially.   A centrally drilled hole in the coal sample allowed the gas to flow out of the chamber in a controlled manner.   The second permeability test apparatus used in this study, was a high pressure triaxial cell, initially built for determining the relative permeability of coal measure rocks under two-phase flow conditions (Indraratna and Haque, 1999; Jasinge, *et al.*, 2011; Perera, *et al.*, 2011). Both methods of testing and the results obtained are the subject of discussion in this paper.

COAL PERMEABILITY TEST WITH MULTI FUNCTION OUTBURST RESEARCH RIG (MFORR)

Apparatus

The Multi function Outburst Research Rig (MFORR) shown in Figure 1, is used to study the permeability of coal from parallel to stratification.   MFORR comprises a number of components which can be utilised for permeability testing with the confining pressure being provided by the applied gas pressure which filters through the coal being tested.   As a multifunction apparatus the MFORR has various components:

- The main apparatus support frame;

- A precision drill;

- A high pressure chamber which has a load cell for measuring the load applied to the samples of coal;

- A pressure transducer for measuring the pressure inside the chamber;

- Flow meters for measuring the gas flow rate;

- Two strain gauges for measuring the vertical and horizontal strains of the coal sample;

- A universal socket for loading a sample of coal vertically into the gas pressure chamber;

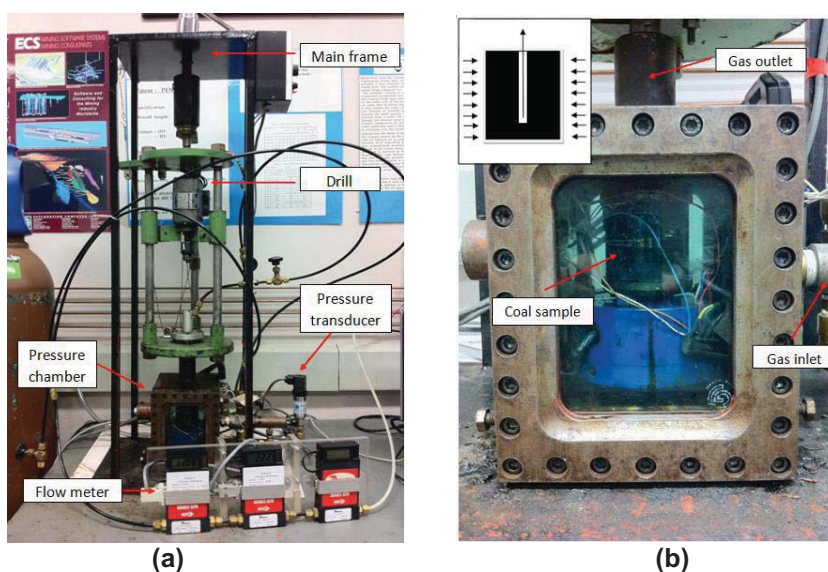- A gas chromatograph (GC);

- A data acquisition system.

(a)   (b)

Figure 1 - Multi Function Outburst Research Rig (MFORR)

The gas pressure chamber containing the coal sample is a hollow rectangular prism of cast iron with removable front and back viewing plates.   The dimensions of the box are 110 mm x 110 mm x 140 mm. The viewing windows are made of 20 mm thick glass in a cast iron frame.   Housed in the chamber is a 1210-BF interfaced load cell with a capacity of 40 kN for monitoring the load applied.

Coal sample preparation

Prior to coring, the lump coal sample from the typical Bulli seam was cast in concrete to form a uniform block for easy coring.   A set of standard core samples with a dimension of 54 mm in diameter and 50 mm in height were bored out of the core block.   A 2 mm diameter hole was drilled in the middle of the cored coal sample to measure the permeability of this apparatus.   Prior to testing, both ends of the prepared specimen were sealed with an adhesive 1 mm thick rubber layer to ensure effective gas flow along radius in the coal.   Figure 2 shows the snapshot of the sample.
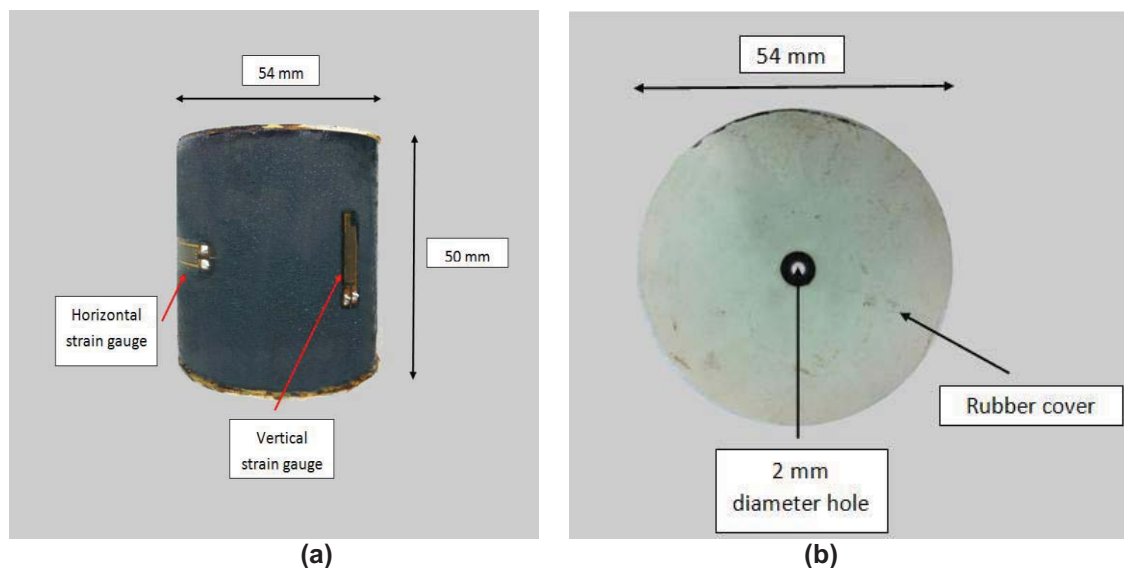

(a)   (b)

Figure 2 - Coal samples for permeability test with MFORR

Testing procedure

The procedure adopted for permeability test consisted of each sample being first mounted in the pressure chamber.   The chamber was then sealed, the system then evacuated to remove air and subsequently repressurised to a predetermined level and maintained steady at that level.   The N_2 gas was allowed to permeate the coal sample and flow out through the central hole which is shown in Figure 1b.   The released gas from the coal flows through a measuring system, consisting of a vacuum pressure sensor and a line of gas flow meters of 0-2 L/min and 0-15 L/min measurement ranges respectively.

The test sequence was followed in steps of varying vertical stress of 1, 2, 3 and 4 MPa.   For each selected vertical loading, confining gas pressures varying between 0.2 MPa to 3 MPa were applied. The load cell, flow meters, pressure transducer and strain gauges were connected to a PC through a data logger for data collection.

Testing results and analysis

The permeability of the sample was calculated using the following Darcy's equation:

$$K = \frac{\mu Q \ln(\frac{r_0}{r_i})}{\pi L (P_1{}^2 - P_2{}^2)} \qquad (1)$$

Where K is the permeability of coal, μ is viscosity of gas, Q is the flow rate of gas, L is the height of the sample, r_o and r_i are the external radius and internal radius of sample, P_1 and P_2 are absolute gas pressure inside and outside of chamber, respectively.

Figure 3 shows the permeability test result with MFORR with N_2 pressurisation. For each of the vertical stress, coal sample permeability decreases with increasing gas pressure and at higher gas pressure, coal permeability stays stable and changes very little, under different vertical stresses. Test results show that the permeability values stay below 2 mD when the applied confining gas pressures became greater than 0.5 MPa.
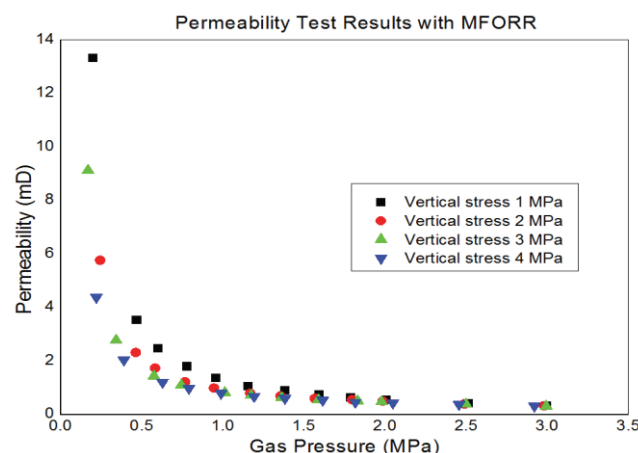

Figure 3 - Coal permeability test result with MFORR

Figure 4 shows coal strain behaviour in the MFORR permeability test. Test results show that the degree of the axial strain both axially and laterally are influenced by the level of pressures that sample being subjected under triaxial environment.

There is an increased compaction of the coal layers parallel to bedding with increased vertical stress due to applied axial loads perpendicular to layering. The degree of axial shrinkage has increased with increasing axial stress as demonstrated in Figure 4a. Also, the level of vertical or axial strain reduction has reduced with the increase in the applied lateral gas confining pressure. The level of lateral/horizontal strain was affected by the level of the applied axial load as well as the confining gas pressure, this time in reverse order. That is, at high vertical stress of 4 MPa, the confining lateral stress was the greatest, while the least applied axial stress contributed to increased maximum lateral strain. Also and irrespective of the level of the axial stress the horizontal stain levels tapered off gradually with gradual increase of the applied confining gas pressure as demonstrate in Figure 4b.

These results clearly demonstrate the coal sample underwent negative volumetric changes or shrinkage with increased confinement pressures axially and laterally, and that the degree of the volumetric changes will be dependent on the level of the applied axial and lateral pressures or stresses.
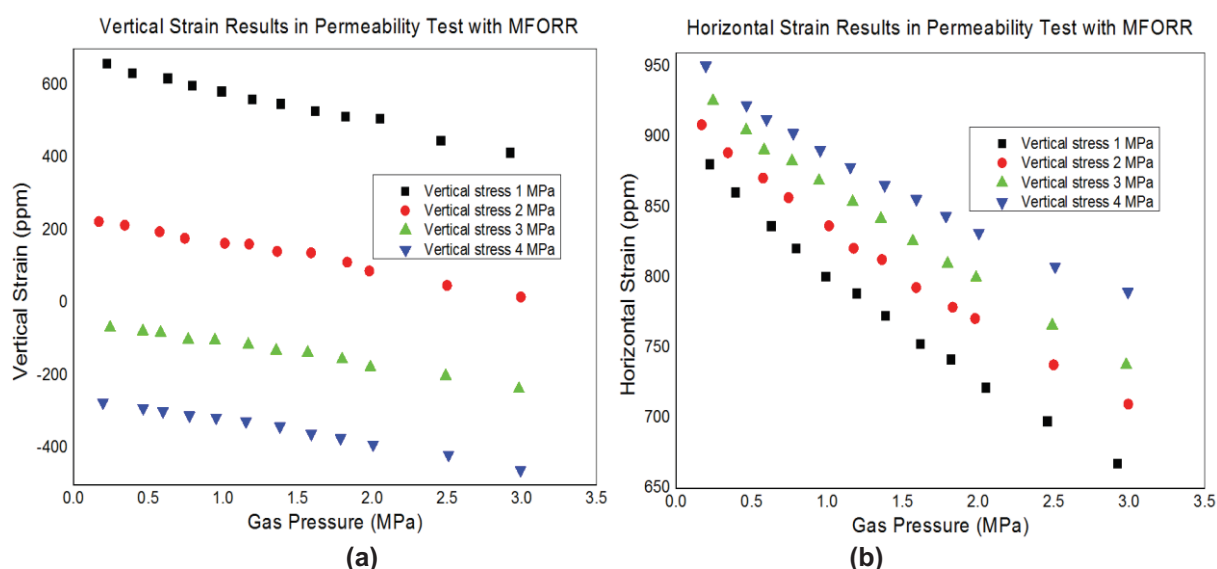

(a)   (b)

Figure 4 - Coal strain behaviour in the permeability test with MFORR

TRIAXIAL PERMEABILITY STUDY WITH TRIAXIAL COMPRESSION APPARATUS

Apparatus

The setup of the triaxial compression apparatus is shown in Figure 5. This apparatus, which can be utilised in normal triaxial permeability test of coal comprises a number of components, including:

- A main apparatus loading system for holding and loading the pressure cell;
- High pressure cell for holding the coal sample in triaxial permeability test;
- A axial loading and measuring device;
- Oil pump for generating and maintaining the confining pressure applied to the coal sample;
- A pressure transducer for measuring the pressure inside the cell;
- A pressure transducer for measuring the pore pressure;
- Flow meters for measuring the gas flow rate;
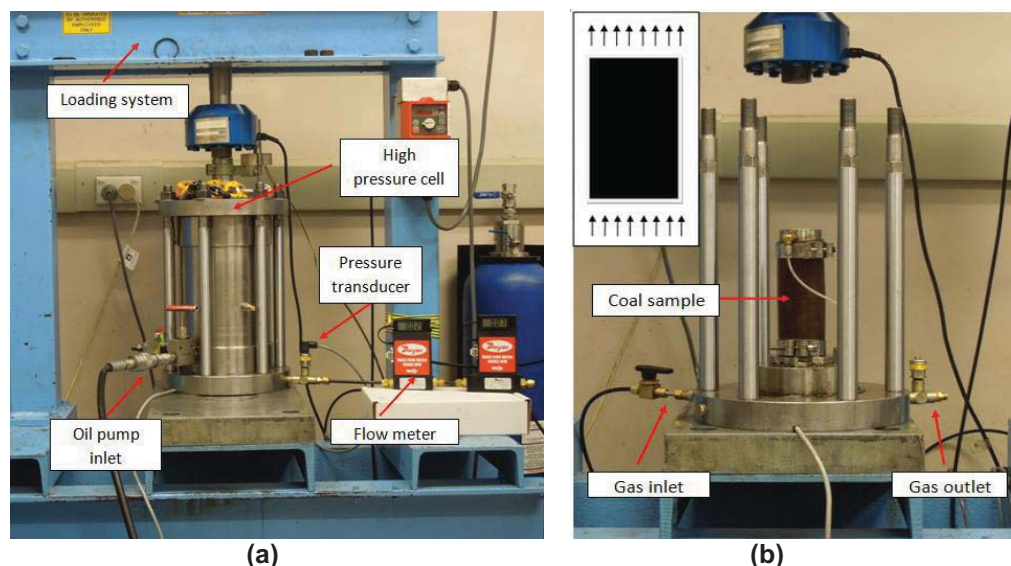- A data acquisition system.

Figure 5 - Triaxial compression apparatus

In this apparatus, the cell pressure is controlled manually by a hydraulic jack and a pressure transducer, which is mounted on the cell to ensure the required confining pressure. As the cell is made of high-yield steel it can withstand a maximum pressure of 150 MPa with a safety factor of two. The cell is capable of carrying out high confining pressure tests, making it suitable to simulate a high *in situ* stress environment in coal measure rocks. The axial load is applied by a servo-controlled compression test machine with the maximum force of 250 kN.

Coal sample preparation

The standard core samples with dimension of 54 mm in diameter and 100 mm in height were drilled from the same lump coal sample as the MFORR permeability test samples, which were also typical Bulli seam coal samples. Figure 6 shows the snapshot of the sample.

Testing procedure

The procedure for conducting each test consisted of the sample being correctly installed inside a membrane, the specimen was placed into the high pressure cell where a small axial load was applied firstly to keep it stable; then oil was pumped into the cell until the cell was filled with oil with both the axial load and confining pressure applied at predesigned values. Subsequently N_2 gas pressure was applied at a predetermined level and N_2 gas flowed through the coal sample from bottom to top which

was shown in Figure 5b. The released gas from the coal flowed through a monitoring system consisting of gas flow meters with 0-2 L/min and 0-15 L/min measurement ranges.

The test sequence was followed in steps, with different vertical stresses of 3, 4, 6 and 8 MPa respectively. The gas pressure was charged initially at 0.2 MPa then increased gradually to higher pressure in steps reaching a maximum of 3 MPa. The load cell, flow meters, pressure transducer were all connected to a PC through a data logger for data collection.
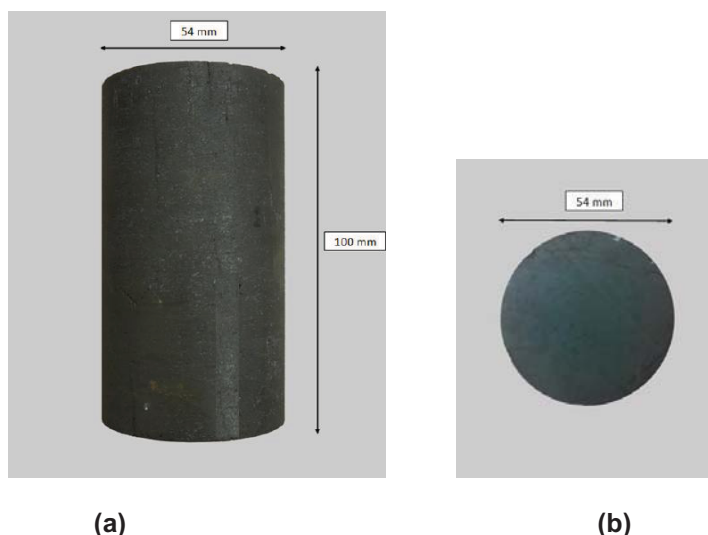

(a)   **(b)**

**Figure 6 - Coal samples for triaxial permeability test with Triaxial Compression Apparatus**

Testing results and analysis

The permeability of the sample was calculated using the following Darcy's equation:

$$K = \frac{2Q\mu LP_2}{A(P_1^2 - P_2^2)} \qquad\qquad (2)$$

Where K is the permeability of coal, μ is viscosity of gas, Q is the flow rate of gas, L is the length of the sample, A is the cross section of specimen, P_1 and P_2 are the inlet and outlet absolute gas pressure, respectively.

Figure 7 shows the triaxial permeability test results with N_2 at different vertical stresses. Tests with a vertical stress of 3, 4, 6 and 8 MPa were examined. For each of the vertical stress, two horizontal stresses were examined, coal sample permeability decreased with the increasing gas pressure. At higher gas pressures, coal permeability stayed constant, a similar trend as with the permeability test with MFORR. At each vertical stress, coal permeability test decreases with the increasing horizontal stress.
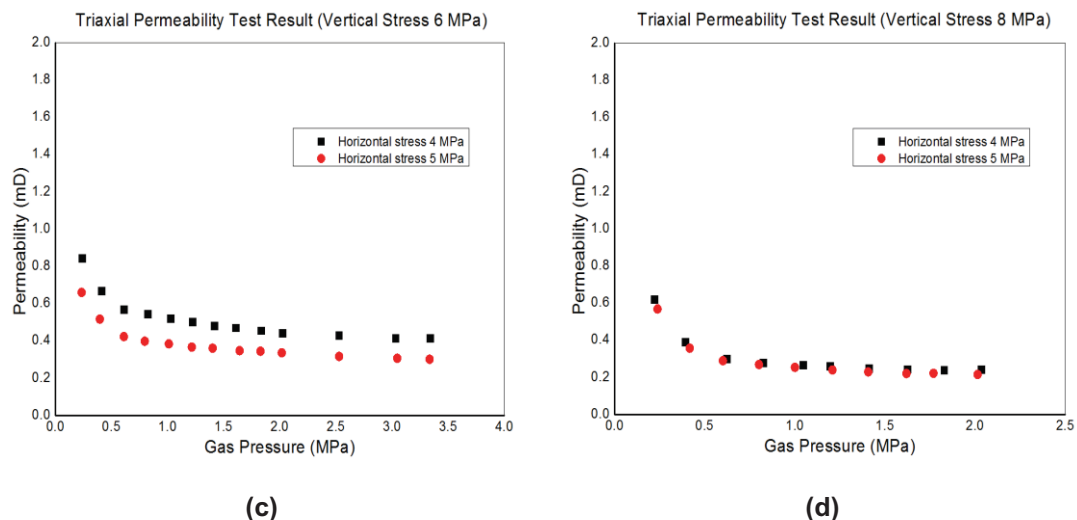

(a)   **(b)**

(c)   (d)
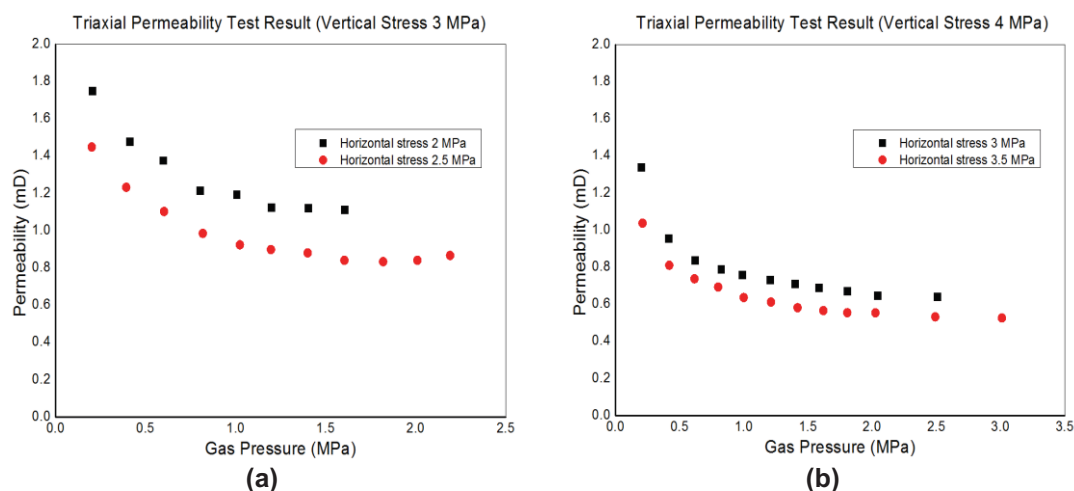
Figure 7 - Coal triaxial permeability test with a certain vertical stress

Figure 8 shows the triaxial permeability test results at a various horizontal stresses.   Tests at horizontal stresses of 4 and 5 MPa are analysed in this study. At each of the horizontal stresses, coal sample permeability decreases with increasing vertical stress.

It can be observed from the tests that the permeability values are well below 2 mD under the triaxial test conditions.
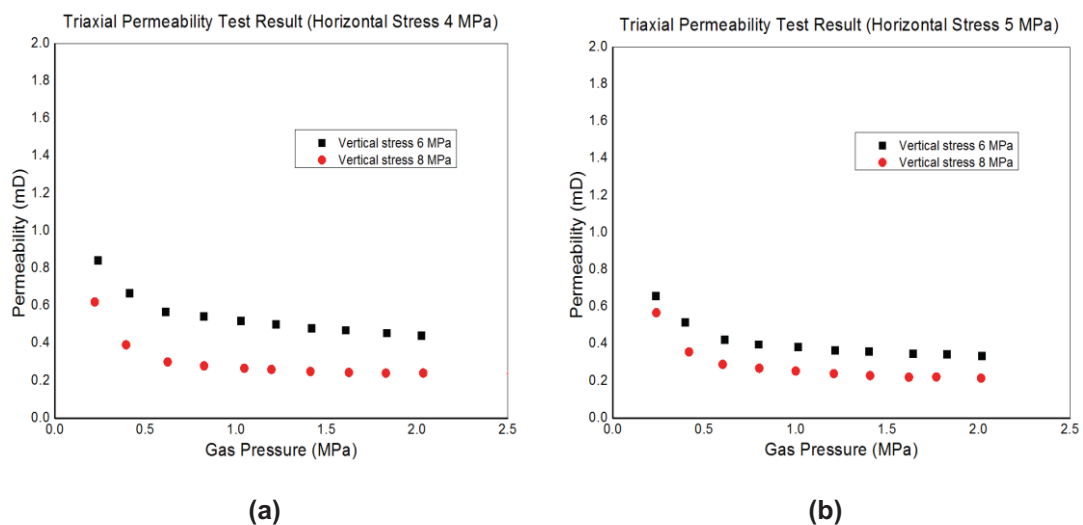

(a)   (b)

Figure 8 - Coal triaxial permeability test with a certain horizontal stress

MFORR PERMEABILITY AND TRIAXIAL PERMEABILITY TEST RESULTS COMPARISON

Figure 9 shows a comparison of the permeability results between the MFORR and triaxial tests at suitable vertical stresses.   Although the results show some significant difference in permeability values at lower confining gas pressure because of the relatively low confining pressure of MFORR test, the permeability converges to a steady level below 2 mD under high triaxial stress conditions portraying the near *in situ* conditions of the Bulli seam. There is no significant mathematical difference between the two different types of testing apparatus and calculation method.

Similar results are confirmed with the other studies, Hayes (1982) reported that the Bulli seam permeability is considerably less than 1 mD. Lingard *et al.* (1984) reported permeability of Australian coals from Appin, West Cliff and Leichhardt collieries that varied from less than 0.1 mD to 100 mD. Recently the Bulli seam permeability was measured using a combination of injection/falloff and step-rate testing methods (Jackson, 2004) and the results from 31 locations of the Bulli seam at West Cliff Colliery

(Fredericks, 2008; Black, 2012), the average *in situ* permeability is 2.2 mD, with the range extending from a low of 0.005 mD to a high of 5.8 mD.
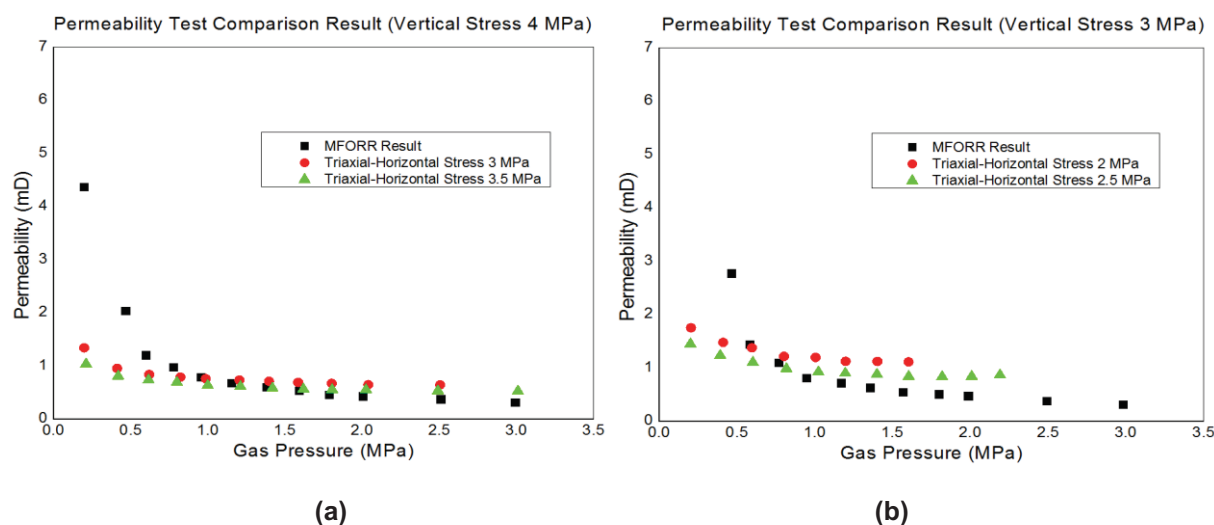

Figure 9 - MFORR permeability and triaxial permeability test results comparison

CONCLUSIONS

Permeability testing with the MFORR can be used to study the relationship between axial stress, gas pressure and coal permeability.   Tests show at each of the vertical stress, coal sample permeability decreases with increasing gas pressure and at higher gas pressure, coal permeability stays stable and its changes under different vertical stress become relatively smaller.

Strain gauge results from the MFORR test clearly demonstrate the coal sample underwent negative volumetric changes or shrinkage with increased confinement pressures axially and laterally.   The degree of the volumetric changes is found to be dependent on the level of the applied axial and lateral pressures or stresses.

Permeability testing using the high pressure conventional Triaxial Compression Apparatus can be used to study the relationship between axial and confining stress, gas pressure and coal permeability under triaxial condition.   Coal sample permeability decreased with the increasing gas pressure.   At higher gas pressures, coal permeability stays constant, a similar trend as with the permeability test with MFORR.

In the permeability test with Triaxial Compression Apparatus, at each vertical stress, coal permeability test decreases with the increasing horizontal stress and at each of the horizontal stress, coal sample permeability decreases with the increasing vertical stress.

It is concluded that there is no significant mathematical difference between the two types of testing apparatus and calculation methods.   Both of the permeability tests are comparable and telly's well with the Bulli coal seam tests result calculation from *in situ* condition.   A permeability of <2 mD should be adopted under high triaxial stress conditions.

ACKNOWLEDGMENT

REFERENCES

Aziz, N and Li-Ming, W, 1999. The effect of sorbed gas on the strength of coal – an experimental study. *Geotechnical and Geological Engineering* 17(3) (Honary eds: Indraratna and Aziz) , pp 387-402.

Black, D, 2012. Factors affecting the drainage of gas from coal and methods to improve drainage effectiveness. PhD thesis (University of Wollongong).
<http://www.uow.edu.au/eng/outburst/pdfs/D%20Black%20PhD%20Thesis.pdf>

Cui, X and Busten, R, 2006. Controls of coal fabric on coalbed gas production and compositional shift in both field production and canister desorption tests, *SPE Journal*, pp 111-119. (SPE-89035).

Farhang, S, 2005. Improving coal mine safety by identifying factors that influence the sudden release of gases in outburst prone zones. PhD thesis (University of Wollongong).

Fredericks, L, 2008. Bulli seam permeability data files - 2003 to 2006, *BHP Billiton Illawarra Coal Exploration - Confidential Test Reports*.

Gillies, A D S, Gray, I and Ham, B, 1995. Measurement of coal permeability using large samples. *International Symposium-CUM-Workshop on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines*, Wollongong, NSW, Australia, pp 317-322.
<http://www.uow.edu.au/eng/outburst/pdfs/C3079%20Final%20Report.pdf>.

Gray, I, 1982. A study of seam gas drainage in Queensland, in *Proceedings of the Symposium on Seam Gas Drainage with Particular Reference to the Working Seam*, (ed: A J Hargraves), Australasian Institute of Mining and Metallurgy - Illawarra Branch, University of Wollongong, Wollongong, Australia, 11-14 May, pp 218-231.

Harpalani, S and Schraufnagel, R A, 1990. Shrinkage of coal matrix with release of gas and its impact on permeability of coal, *Fuel*, Vol. 69, pp 551-556.

Hayes, P J, 1982. Factors affecting gas release from the working seam, in *Proceedings of the seam gas drainage with particular reference to the working seam*, organised by the Aus IMM –Illawarra branch, University of Wollongong, May (Edit. A J Hargraves), pp 62-69,
<http://www.uow.edu.au/eng/outburst/presentations_publications/ausimm_1982/P.J.Hayes.PDF>

Indraratna, B and Haque, A, 1999. Triaxial equipment for measuring the permeability nd strength of intact and fractured rocks, *Geoptechnique* 49, pp 515-521.

Jackson, M, 2004. Permeability testing procedure, BHP Billiton Illawarra Coal Exploration/Coal Bed Methane, *Internal Operating Procedure, document reference - CBM-12-010*.

Jasinge, D,Ranjith, P G and Choi, S K, 2011. Effects of effective stress changes on permeability of Latrobe valley brown coal. *Fuel* 90(3), pp 1292-1300.

Jones, A H, Ahmed, U, Abou-Sayed, A S, Mahyera, A and Sakashita, B, 1982. Fractured vertical wells versus horizontal boreholes for methane drainage in advance of mining U.S. coals, in *Proceedings of the Symposium on Seam Gas Drainage with Particular Reference to the Working Seam*, (ed: A J Hargraves), Australasian Institute of Mining and Metallurgy - Illawarra Branch, University of Wollongong, Wollongong, Australia, pp 172-201.

Lamarre, R A, 2007. Downhole geomechanical analysis of critical desorption pressure and gas content for carbonaceous reservoirs, *SPE Annual Technical Workshop on Coalbed Methane*, Society of Petroleum Engineers, Durango, Colorado, 31p. (SPE-111091).

Lama, R D, 1995. Effect of stress, gas pressure and vacuum on permeability of bulli coal samples. *International Symposium-CUM-Workshop on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines*, Wollongong, NSW, Australia, 293-301.
<http://www.uow.edu.au/eng/outburst/pdfs/C3079%20Final%20Report.pdf>

Lingard, P S, Phillips, H R, Doig, I D, 1984. Laboratory studies of sorption characteristics and permeability of triaxially stressed samples. *Proceeding 3rd Int. cong. on mine ventilation*, Harrogate, pp 143-150.

Nakajima, I, Asakura, Yang, Q and Omai, T, 1995. Effectof earth tempretureon gas permeability of stressed coal, *International Symposium-CUM-Workshop on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines*, Wollongong, NSW, Australia, pp 2323-330.
<http://www.uow.edu.au/eng/outburst/pdfs/C3079%20Final%20Report.pdf>

Osisanya, S A and Schaffitzel, R F, 1996. A review of horizontal drilling and completion techniques for recovery of coalbed methane. SPE International Conference on Horizontal Well Technology, *Society of Petroleum Engineers*, Calgary, Canada, 13p. (SPE-37131).

Perera, M S A, Ranjith, P G, Choi, S K and Airey, D, 2011. The effects of sub-critical and super-critical carbon dioxide adsorption-induced coal matrix swelling on the permeability of naturally fractured black coal. *Energy* 36(11), pp 6442-6450.

Zutshi, Z and Harpalani, S, 2005. Gas flow characterization of Illinois coal: assessment for recovery of coalbed methane and carbon sequestration potential, in *Proceedings of the 2005 International Coalbed Methane Symposium*, University of Alabama, Tuscaloosa, paper no.0514,10p.