

PERMEABILITY AND VOLUMETRIC CHANGES IN COAL UNDER DIFFERENT TEST ENVIRONMENT

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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. Two different types of permeability apparatus were used in this study. The methods of permeability testing of coal under different triaxial conditions are discussed. Permeability testing of the Bulli seam coal with N_2 is described. The laboratory test results were found to be in agreement with the calculated permeability values.

KEYWORDS: coal mine gas, coal permeability, volumetric changes

1. 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 measurement 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, 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. (1982), Lama (1995), Gillies et al. (1995) and Nakajima 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.

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 ten mines in Australia. Difficulties associated with permeability determination in the laboratory or in the field experimentation, are mainly due to the fact that 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 was carried out using a Multi Function Outburst Research Rig (MFORR) which was previously reported by Lama (1995), Aziz and Li (1999) and Sereshki (2005), and more recently by Zhang (2013). 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 testing 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.

2. GEOLOGY

The experimental study of N₂ injection was carried out on coal samples obtained from different mines operating in the Bulli Seam. The Bulli seam is stratigraphically the uppermost seam in the Illawarra coal measures, of Sydney Basin, which belong to Permian and Triassic era. It lies at variable depth ranging between 350 m in the east, near the coast areas, down to 550 m to the west with a regional dip of approximately 1.5° toward the west and north west. The Bulli coal is high quality coking coal with volatile matters ranges from 18-23 percent (air dried), the ash level varies between 8-10 % (air dried), and the sulphur content is low at around 0.3 percent, the mineral content averages around 4 %. The vitrinite content is moderate at 45 %, the inertinite content is about 50 % and vitrinite reflectance at around 1.3. The permeability of coal varies between 0.5 to 6.0 mD. The permeability values were determined both *in situ* and in the laboratory (Lingard et al., 1982; Sereshki, 2005; Black and Aziz, 2010). The permeability of the Bulli coal varies with low permeability zones characterized as being hard to drain with high concentration of CO₂ gas. No attempt is made to report on the permeability coefficient by mathematical modeling characterising transmission and transport properties of gas, and flow character, as it beyond the scope of this paper.

The Bulli coal seam gas composition varies significantly throughout the Illawarra Coalfield, with the depth of cover and proximity to geological structures (faults and dykes). The changes in seam gas from predominantly CH₄ to predominantly CO₂ have been noted on a regional basis. Generally CO₂ increases to the north and to the west. The high CO₂ gas composition area with various gas content in a specific mine site was reported recently by Zhang et al., (2013). However, for each mine operating the Bulli seam in the Illawarra Coal measures, the potential gas composition to vary considerably is well recognised. The maximum desorbable gas content varies from 1-3 m³/t in the coastal areas in the east, to about 21 m³/t at depths of up to 550 m towards the west and north west.

The gas content and gas composition of the Bulli seam of the area varies within wide limits. In the seam closer to the outcrop, the gas content is relatively low.

As the distance from the outcrop increase, the gas content increases. The maximum desorbable gas content as measured in the coal seam varied between 1-3 m³/t in the coastal areas at a depth of 350 m and as much as 21 m³/t at greater depths of up to 550 M. The composition of the gas varies widely too. Normally the gases associated with the Bulli seam include both CH₄ and CO₂.

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

3.1. APPARATUS

The Multi function Outburst Research Rig (MFORR) shown in Figure 1, was used to study the permeability of coal from parallel to its 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

3.2. COAL SAMPLE PREPARATION

Prior to coring, a lump of coal sample from a local mine operating the Bulli seam of Sydney Basis, of NSW, 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 coal 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 parallel ends of the prepared coal 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.

3.3. 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

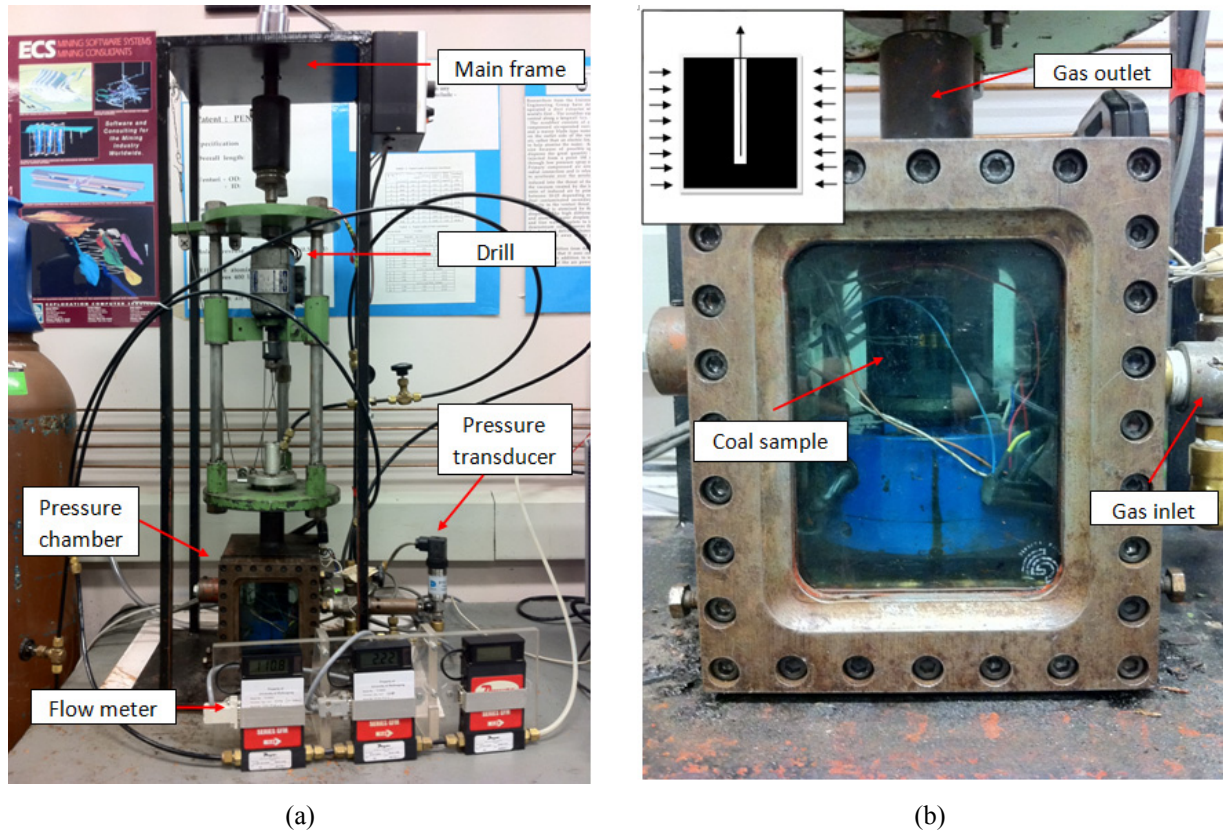


Fig. 1 Multi Function Outburst Research Rig (MFORR).

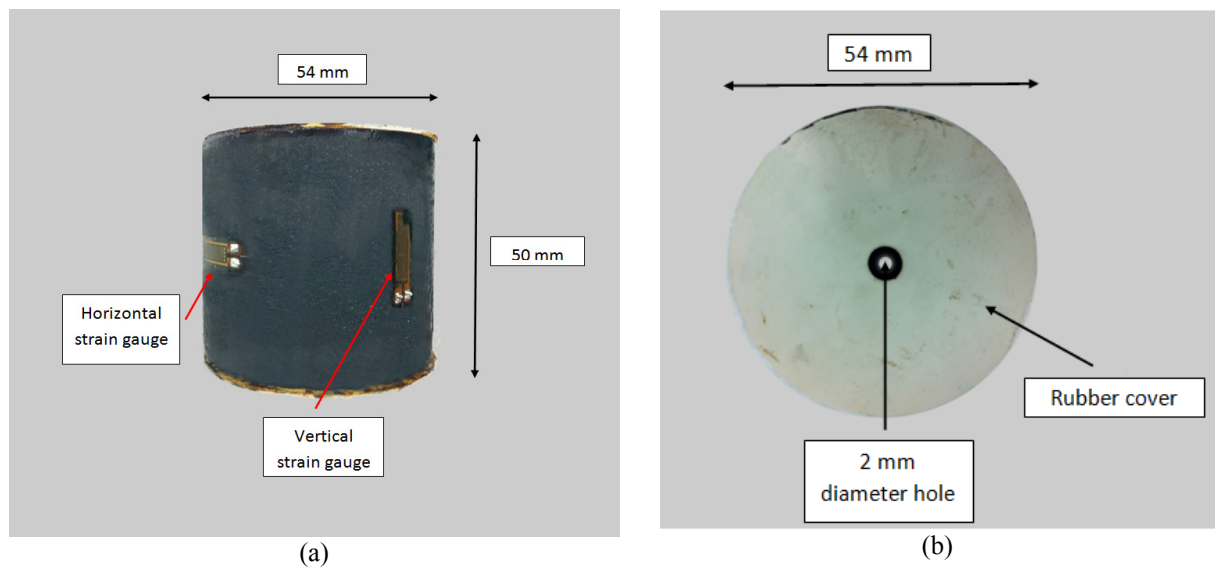


Fig. 2 Coal samples for permeability test with MFORR.

steady at that level. N_2 gas was then 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 flowmeters 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, flowmeters, pressure transducer and strain gauges were connected to a PC through a data logger for data collection.

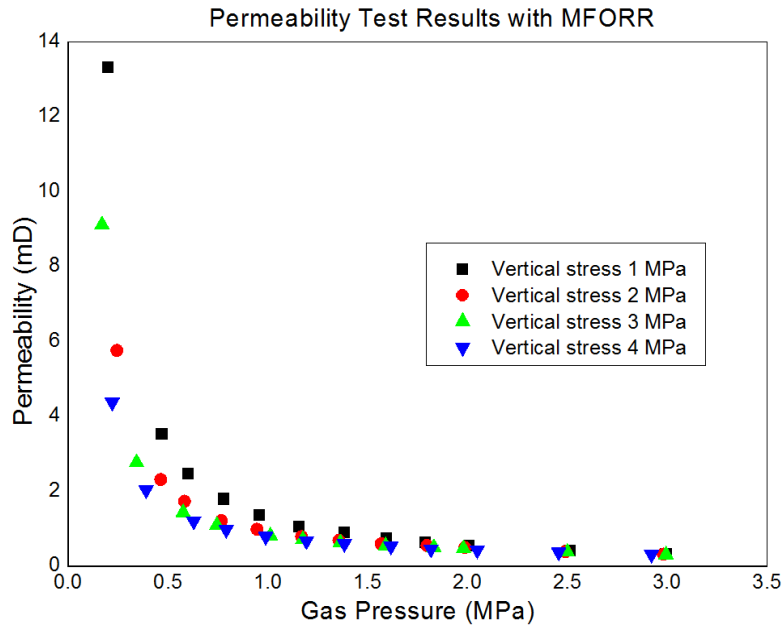


Fig. 3 Coal permeability test result with MFORR.

3.4. TESTING RESULTS AND ANALYSIS

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

$$K = \frac{\mu Q \ln\left(\frac{r_o}{r_i}\right)}{\pi L (P_1^2 - P_2^2)} \quad (1)$$

Where K is the permeability of coal, μ is the 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 apparatus, which is being pressurised by N_2 gas, at different applied vertical stress levels. For each of the vertical stress level, the 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. The test results show that the permeability values stay below 2 mD when the applied confining gas pressures became greater than 0.5 MPa.

Figure 4 shows coal strain behaviour in the MFORR permeability test. Test results show that the degree of strain, both axially and laterally, is influenced by the level of pressure that the sample being subjected to 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 strain 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 undergoing 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.

4. TRIAXIAL PERMEABILITY STUDY WITH TRIAXIAL COMPRESSION APPARATUS

4.1. 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

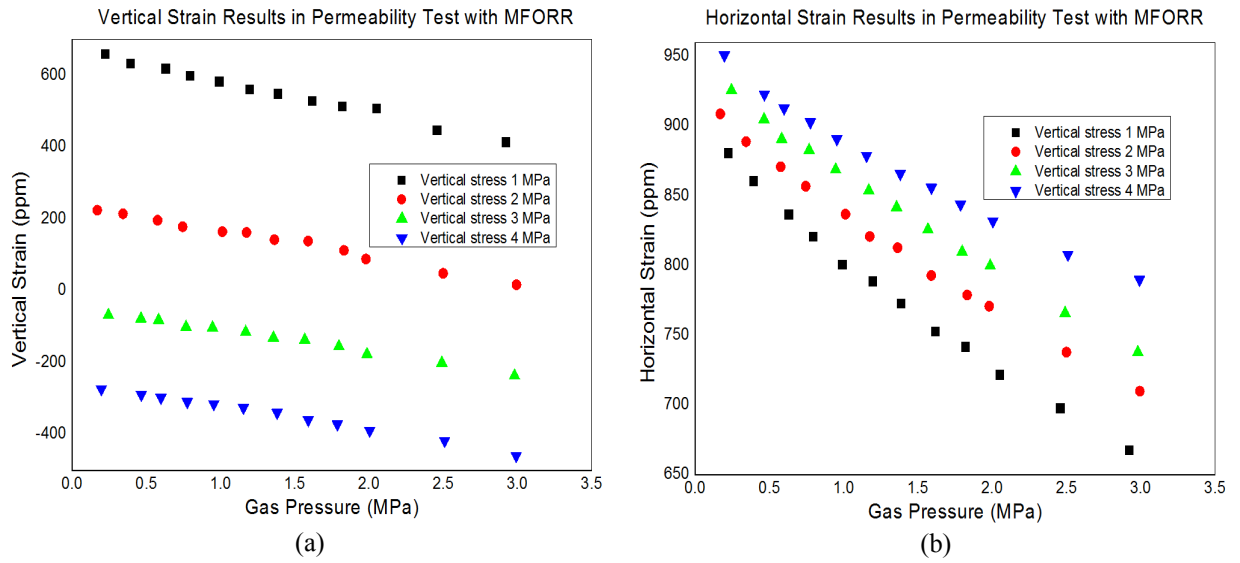


Fig. 4 Coal strain behaviour in the permeability test with MFORR.

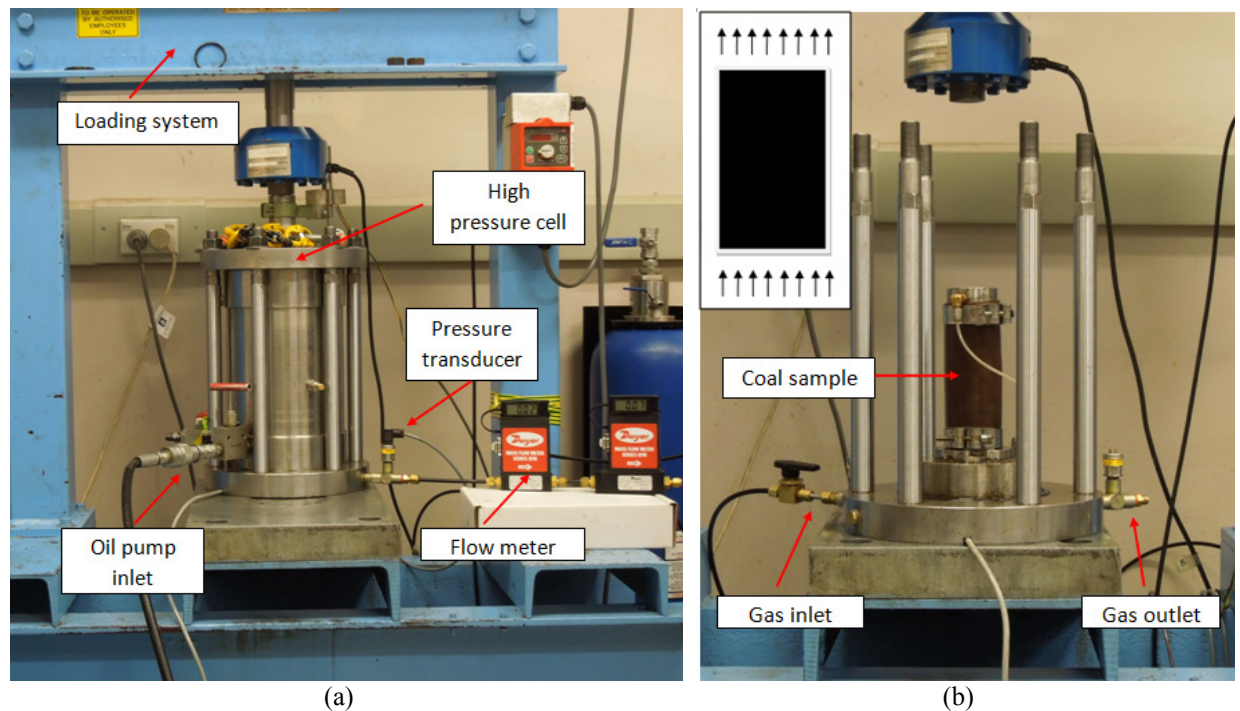


Fig. 5 Triaxial Compression Apparatus.

- Flow meters for measuring the gas flow rate
- A data acquisition system

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 testing machine with the maximum force of 250 kN.

4.2. 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.

4.3. 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

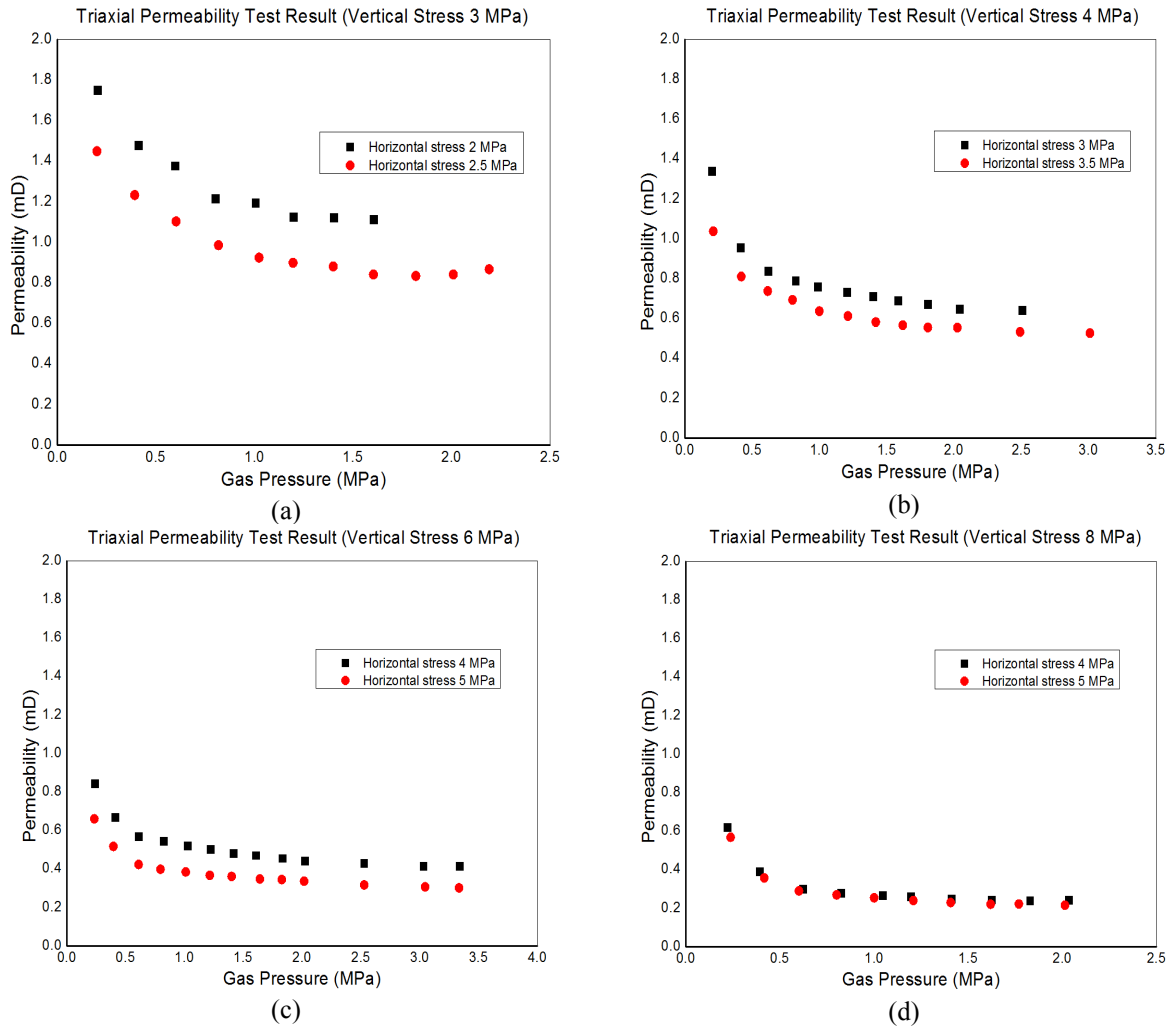


Fig. 6 Coal triaxial permeability test with a certain vertical stress.

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 flowmeters 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, flowmeters, a pressure transducer were all connected to a PC through a data logger for data collection.

4.4. TESTING RESULTS AND ANALYSIS

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

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

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 6 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.

Figure 7 shows the triaxial permeability test results at a certain horizontal stress. Tests at horizontal stress of 4 and 5 MPa are analysed in this study. At each of the horizontal stress, coal sample permeability decreases with the increasing vertical stress. It can be observed from the tests that the permeability values are well below 2 mD under the triaxial test conditions.

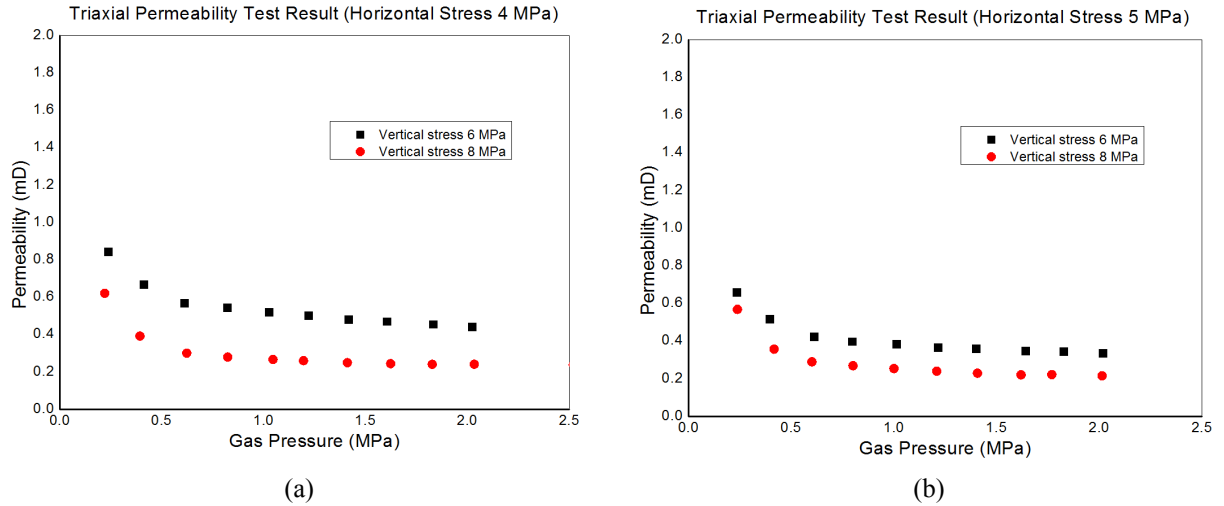


Fig. 7 Coal triaxial permeability test with a certain horizontal stress.

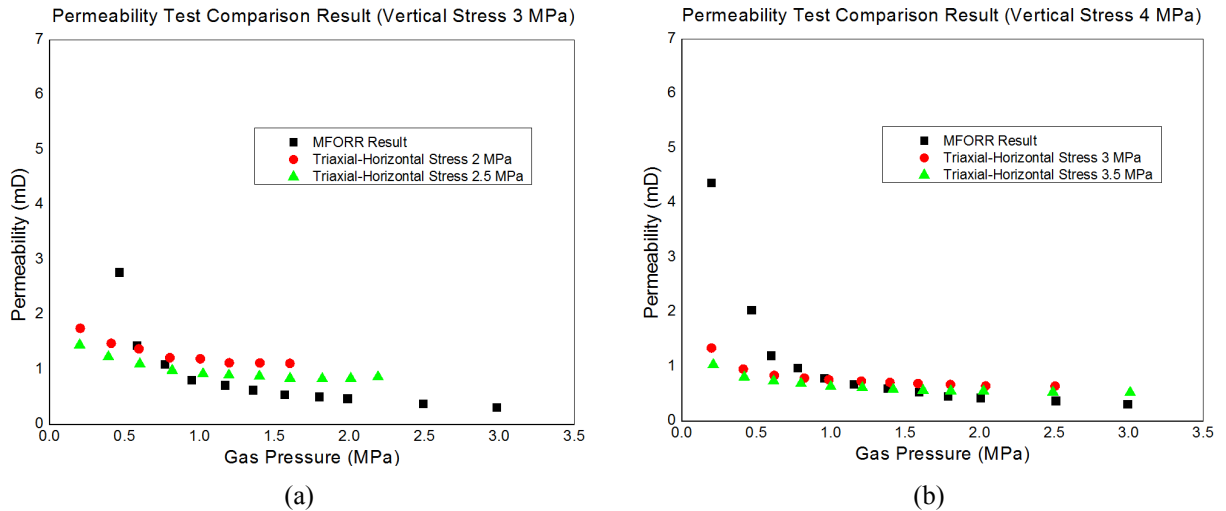


Fig. 8 MFORR permeability and triaxial permeability test results comparison.

5. MFORR PERMEABILITY AND TRIAXIAL PERMEABILITY TEST RESULTS COMPARISON

Figure 8 shows a comparison of the permeability results between the MFORR and triaxial tests at various 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. No significant mathematical difference between the two different types of testing apparatus and calculation method were evident.

Similar results are confirmed with the other studies; Hayes (1982) reported that the Bulli seam coal permeability was considerably less than 1 mD. Lingard et al. (1982) 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 coal 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 and Black, 2012) showed the average *in situ* permeability of coal as 2.2 mD, with the range extending from a low of 0.005 mD to a high of 5.8 mD.

6. CONCLUSIONS

Permeability testing with the MFORR show that coal permeability decreases with increasing gas pressure. At higher gas pressures, coal permeability stays stable and changes little with changes in under differing operating range vertical stress conditions of the MFORR.

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.

Under Triaxial Compression Apparatus, at each vertical stress, coal permeability decreases with the increasing horizontal stress. However, coal permeability decreases with the increasing vertical stress.

There is no significant mathematical difference between the two types of testing apparatus and calculation methods. Both permeability test results are comparable and tally'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.

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