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Nazanin Nourifard
University of Wollongong

Lei Zhang
University of Wollongong, leiz@uow.edu.au

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

Jan Nemcik
University of Wollongong, jnemcik@uow.edu.au

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STUDY OF PERMEABILITY OF COAL SAMPLES SUBJECTED TO CONFINING PRESSURES

Nazanin Nourifard[1], Lei Zhang[1&2], Naj Aziz[1] and Jan Nemcik[1]

ABSTRACT: Permeability is assessment of the ability of rock to transmit fluid flow through the rock body. It can be affected by rock structure due to the grain size, formation and the pressure or concentration gradient existing within and across it. Past studies focused on the relationship between permeability and axial stress on rock, and there has been limited research on the impact of circumferential stress and volumetric deformation on permeability. A programme of laboratory tests was conducted on coal samples to evaluate the permeability of coal under different confining pressures. A specialised permeability apparatus known as Multi-Functional Outburst Research Rig (MFORR), was used to study rock permeability under various confining pressures. Methane permeability tests on cylindrical coal samples were conducted at varying axial stress up to 3 MPa and confining CH_4 gas pressures between 0.2 MPa and 3 MPa. It was found that by increasing the confining gas pressure the permeability value decreased in elastic phase and maintained an almost constant value at gas pressures greater than 2 MPa. The results show that the permeability of coal sample under triaxial compression tend to decrease with the increase in stress.

INTRODUCTION

Permeability is one of the most important parameters that affect gas production rates and reservoir recovery of coal seams (Shi and Durucan, 2003; Wallace and Bruce, 1990). Coal is generally defined as a dual porosity rock, containing both macro pore and micro pore systems; the macro pore system consists of a naturally occurring network of fractures called cleats, serving as the primary pathways for gas transport. The micro porosity of coal is within the coal matrix blocks, surrounded and separated by cleats, consisting of large number of interconnected pores that serve as the storehouse for methane in adsorbed form (Mitra, *et al.*, 2012).

Permeability has a significant impact on the ability of a coal seam to produce gas. A recent study by Zhang (2012), examining factors contributing to effective drainage of gas from coal by Multi-Functional Outburst Research Rig (MFORR), found a significant lack of information on coal permeability in comparison with other parameters. Accordingly, research on coal permeability is ongoing, and this study forms a part of such endeavour to improve the knowledge about coal permeability and improve both the method and the apparatus assembly. The main issue is to choose a proper testing method, which fulfils the need for a better understanding of the permeability in permeable rock formations like coal and coarse grained rocks (Nourifard 2014).

EXPERIMENTAL PROCEDURE

Instrumentation

As the name suggests the MFORR enables studies to be carried out on coal/rock Uniaxial Compressive Strength (UCS); Tensile Strength (TS); the effect of gas pressure on coal/rock load bearing capacity; coal drillabilityand permeability and volumetrics changes under triaxial conditions. The equipment consists of the following 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

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[1] *School of Civil, Mining and Environmental Engineering University of Wollongong, Wollongong, Australia, 2522, E-mail:naj@uow.edu.au*
[2] *CUMT*

- 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), and
- A data acquisition system

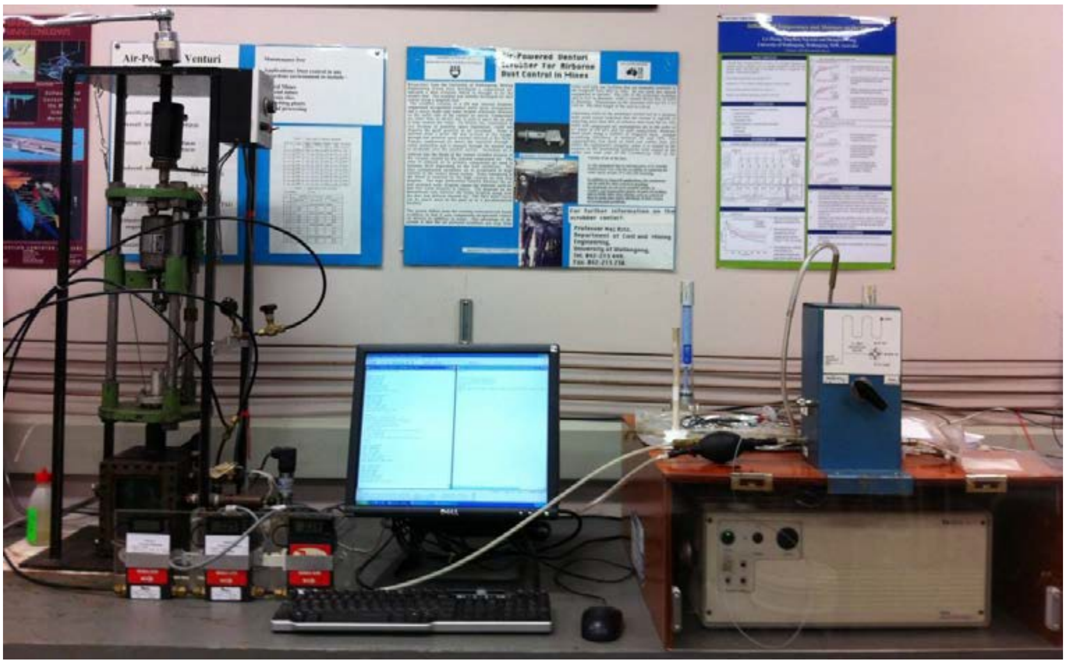

Figure 1: Multi-Function Outburst Research Rig with GC (Zhang, 2012)

The main frame of the apparatus is made of a sturdy steel structure, which houses the gas chamber and universal thrust connector. The gas pressure chamber 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 40 KN load cell capacity for monitoring the load applied.

Gas permeability tests were carried out on specially prepared coal samples 61 mm in diameter and 40 mm in height. The sample holding plates within the apparatus were widened from the initial diameter of 50 mm to 61 mm to accommodate larger diameter samples. A 3 mm diameter hole was drilled in the middle of each of the coal samples. Drilling was carried out perpendicular to coal bedding/layering to allow the pressurise gas to flow laterally through coal beddings. Before testing, both flat end-surfaces of the tested coal samples were sealed with thin rubber gasket pieces to ensure that the gas penetrated along the coal in a radial direction only into the central hole. Figure 2 shows the snapshot of one of the specimens ready to be tested, and Figure 3 shows coal sample sealed in triaxial pressure chamber and a general view of the MFORR

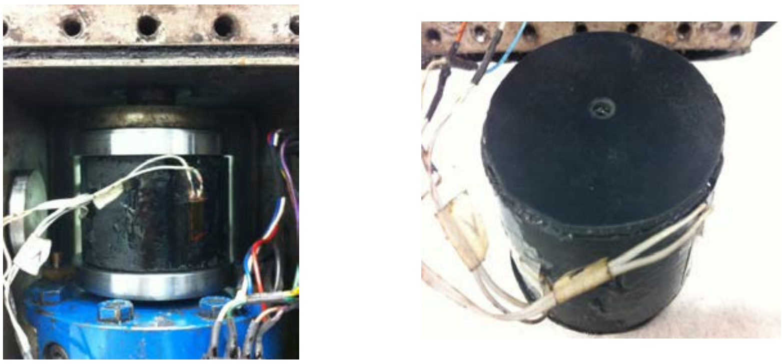

Figure 2: Coal samples for triaxial permeability test with MFOR

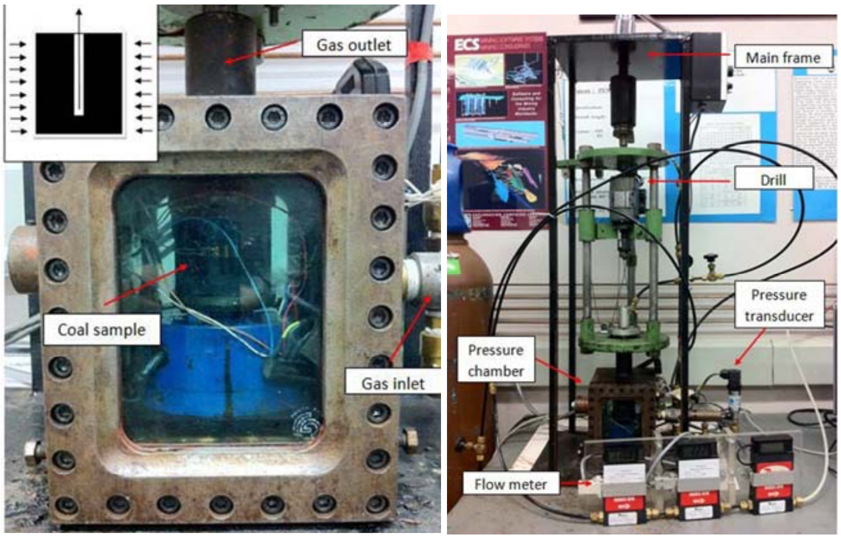

Figure 3: Coal specimen sealed in pressure chamber and Multi-Function Outburst Research Rig (MFORR)

The procedure for conducting each test consisted of mounting each tested sample in the pressure chamber. The loaded chamber was sealed, then vacuumed to remove air and subsequently re-pressurised to a predetermined level and maintained at that level. CH_4 gas was allowed to permeate the coal sample and flow out through the central hole. The released gas from the coal flowed through a measuring system consisting of a vacuum pressure sensor and gas flow meters with 0-2 L/min and 0-15 L/min measurement ranges.

The test sequence was followed in steps with varying vertical stress of 1, 2 and 3 MPa and gas pressure ranging from 0.2 MPa to 3 MPa. The load cell, flow meters, pressure transducer and strain gauges were connected to a computer through a data logger for data collection.

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

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

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_0 is the external radius of the sample and r_i, is the internal radius of the small centrally drilled hole, P_1 and P_2 are the absolute gas pressures inside and outside of chamber, respectively.

RESULTS AND DISCUSSION

Permeability analysis of coal specimens

Permeability values of all tests are shown inTable 1. The results were consistent for all tested coal samples. In general, the tests showed that the coal permeability decreases with increasing gas pressure and applied vertical load/stress. As the flow meter range was limited to 15 L/min maximum, in some of the coal permeability tests, coal permeability results could not be obtained above the measurement range of the flow meter. The consistent behaviour for all tested coal specimens indicated a reduction in permeability with increasing gas pressure. As the axial and confining stress increased, the gradual closure of pore and cleat within the coal reduced its permeability. When the vertical stress began to increase from 1 MPa to 2 MPa, the permeability of coal reduced significantly in all tested coal specimens. Test results indicate that the permeability values stay below 1 mD, when applied confining gas pressures exceed 0.5 MPa at the axial stress of 3 MPa. This is clearly shown in Figures 4 to 9. However, one sample, No 383413 (Figure 7) was very permeable even at the applied vertical stress of 3 MPa. High permeability values at 3 MPa vertical stress is attributed to the crack enlargement and possible sample strength failure in compression.

Table 1: permeability of tested samples in both perpendicular and parallel to beddings

Coal specimen	Permeability (mD) at 1 MPa axial load	Permeability (mD) at 2 MPa axial load	Permeability (mD) at 3 MPa axial load
383404	0.863	0.692	0.589
383408	27.142	13.326	0.700
383410	8.154	0.673	0.512
383413	25.091	14.017	10.121
383416	74.202	13.052	2.160
383418	254.466	51.522	-

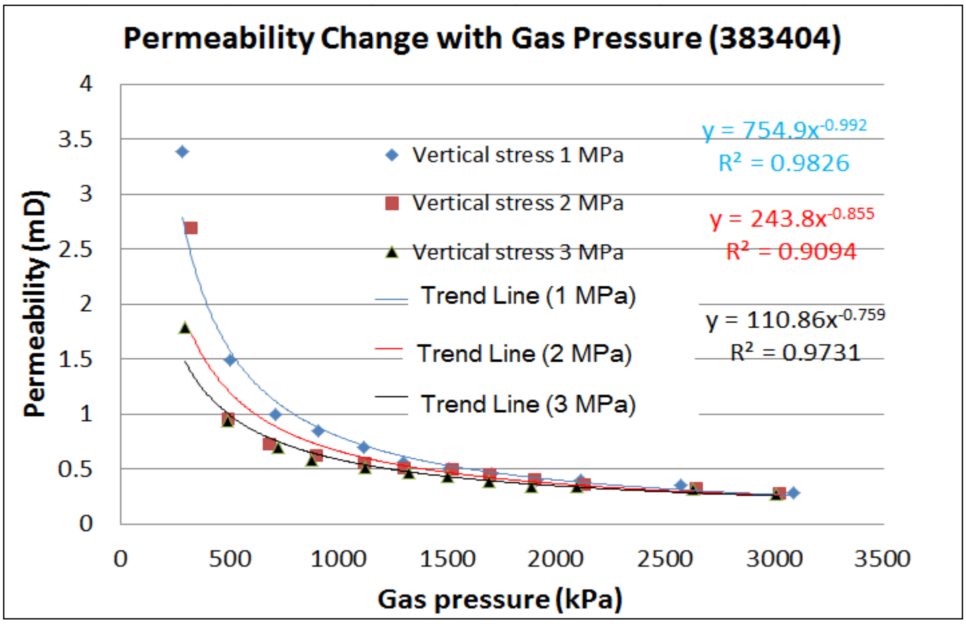

Figure 4: Permeability change for coal specimen no 383404

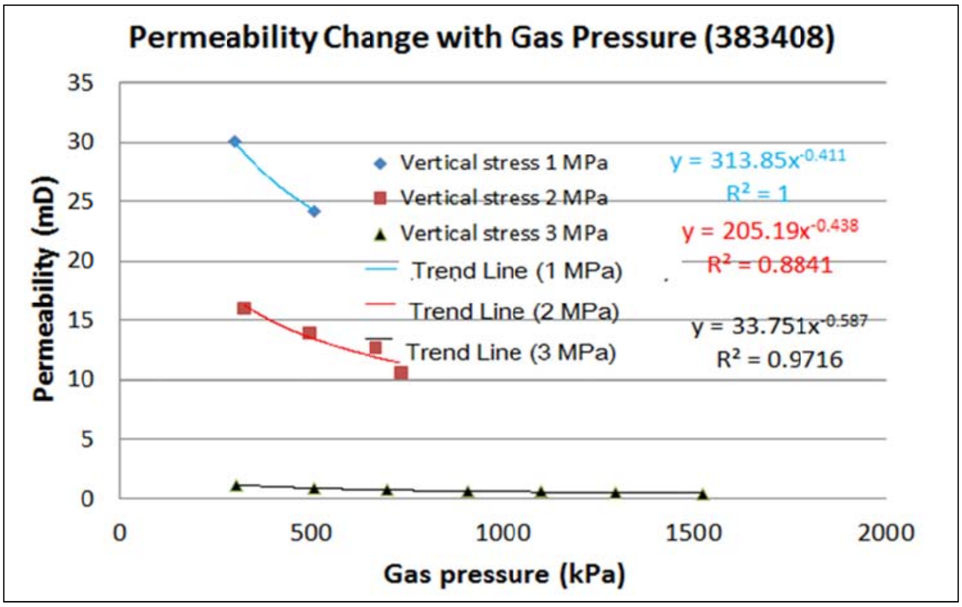

Figure 5: Permeability change for coal specimen no 383408

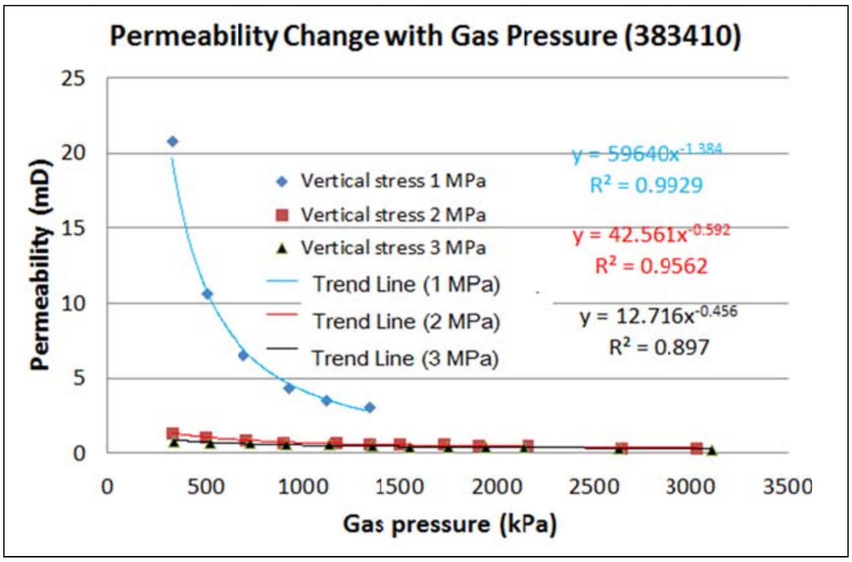

Figure 6: Permeability change for coal specimen no 383410

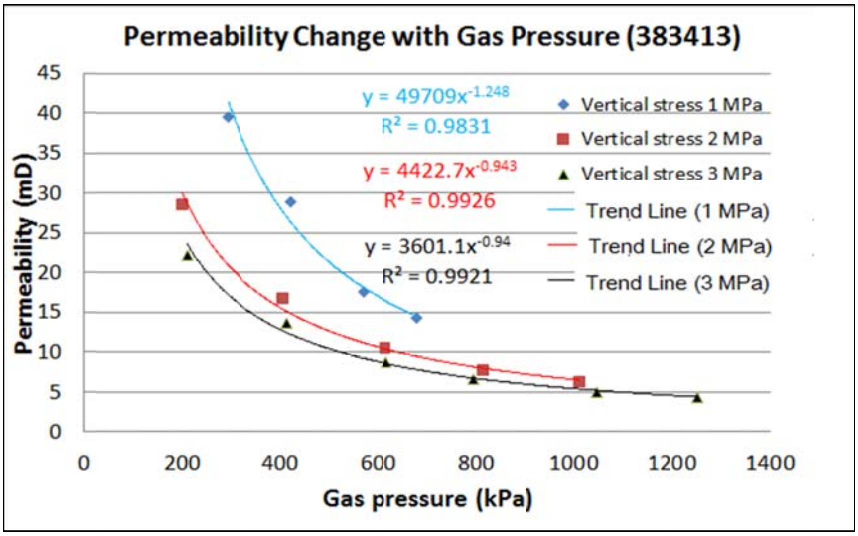

Figure 7: Permeability change for coal specimen no 383413

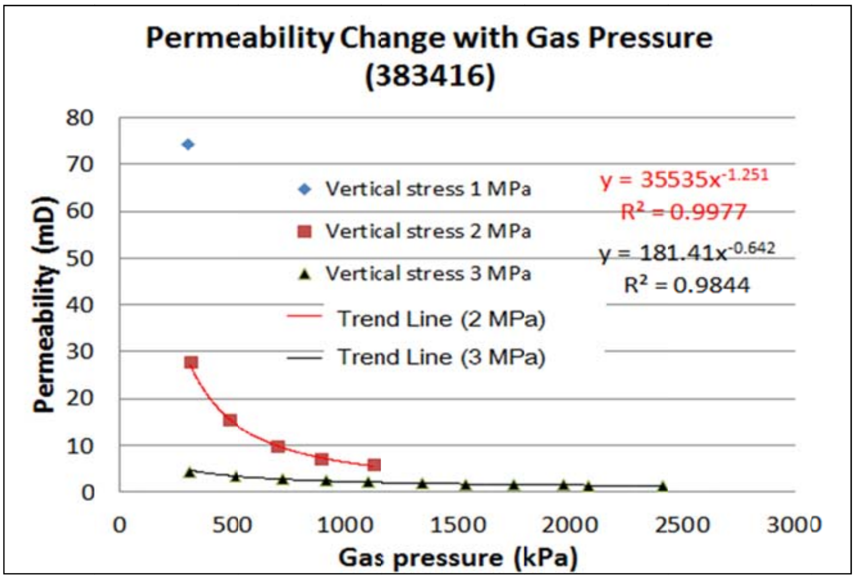

Figure 8: Permeability change for coal specimen no 383416

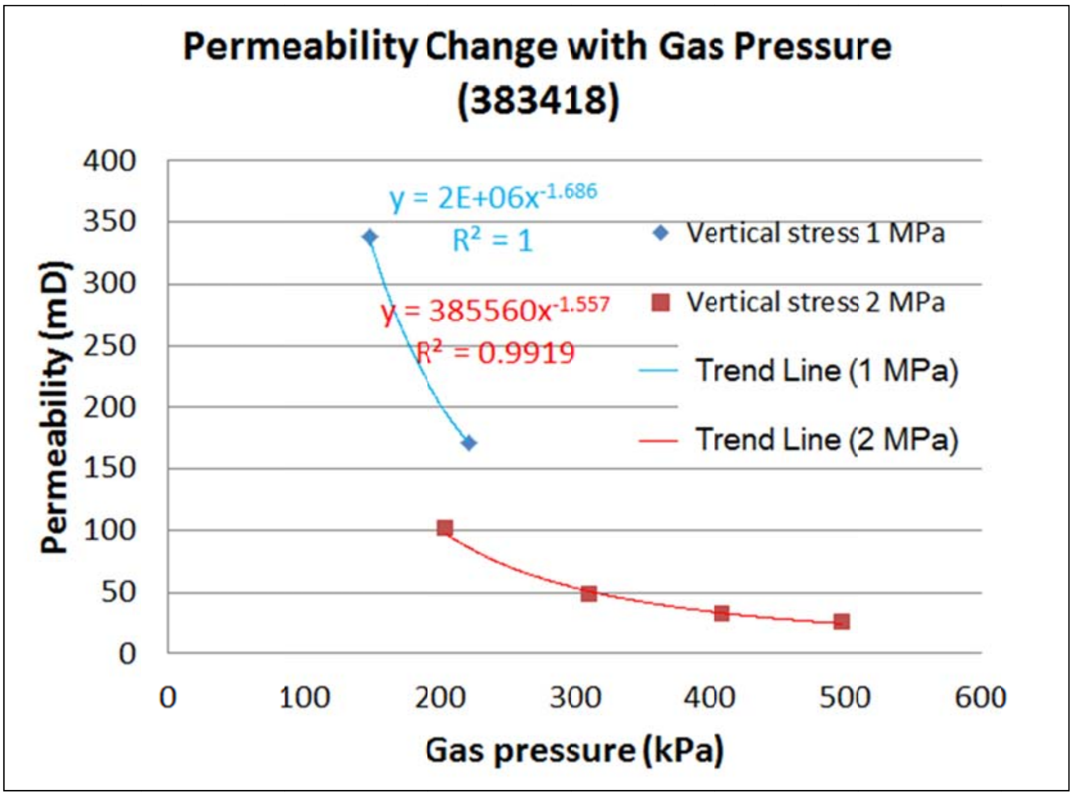

Figure 9: Permeability change for coal specimen no 383418

Examination of the vertically loaded coal samples subjected to the external gas pressure in the pressure chamber clearly showed that the permeability of coal specimens decreased with increased vertical load. There is no doubt that the introduction of methane contributed to the sorption of methane molecules in the coal matrix, which in turn swells the coal matrix and decreases it's the porosity.

A positive value of volumetric deformation indicates swelling and expansion of the tested specimens, and a negative value indicates shrinkage. The changes in horizontal strain were higher than the vertical strain. Lower vertical strain is due to axial loading of the sample.

The permeability changes can be analysed from three stages of the volumetric strain of tested coal specimens. During the first stage, the rock specimen is squeezed with the permeability decreasing rapidly at the beginning of the test. In the second stage, the specimen starts to swell, while in the last stage the samples continued to shrink with increasing axial load. The lowest permeability rate occurred at the last stage of the test at higher axial load and prior to coal failure at around 3 MPa.

Permeability classification of tested coal specimens

According to Palmer (2010) on of Coal Bed Methane (CBM) well completion, coal/rock permeability can be classified into the following categories as shown in Figure 10.

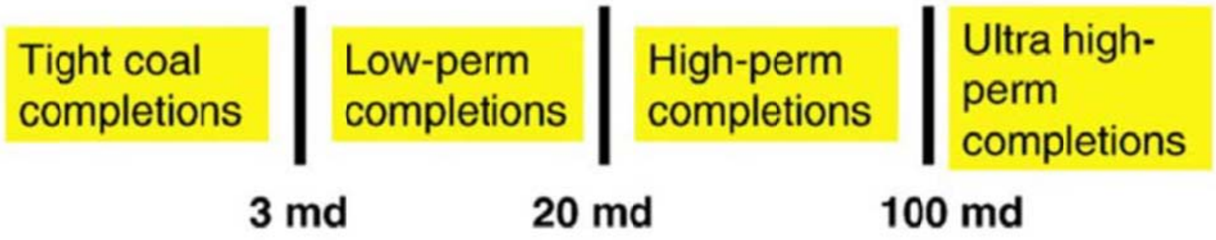

Figure 10: Permeability bands for CBM well completions (after Palmer, 2010)

According to Palmer (2010), the permeability of tested coal specimens can fall into the following classified categories as shown in Table 3, which shows the majority of tested specimens being considered as high permeability.

Table 2: Palmer permeability classification of the tested coal

Coal specimen no	Permeability (mD) On 2 MPa axial load average	Permeability (mD) On 3 MPa axial load average	Palmer classification
383404	0.692	0.589	Tight coal completions
383408	13.326	0.700	Tight coal completions to low permeability completions
383410	0.673	0.512	Tight coal completions
383413	14.017	10.121	low permeability completions
383416	13.052	2.160	Tight coal completions to low permeability completions
383418	51.522	-	High permeability

CONCLUSIONS

Through the study of permeability in coal samples under different confining pressures, the following conclusions have been made:

- Permeability rate of coals under triaxial compression varies by the type and nature of the matrix structure. In general, higher stress environment decreases the permeability.
- Coal sample permeability decreases with increasing gas pressure and at higher gas pressure, coal permeability stays stable and undergoes minor changes under vertical stress above 2 MPa.
- Strain gauge results from the MFORR test showed that coal samples experience negative volumetric changes or shrinkage with increased confinement pressures, both axially and laterally. The degree of the volumetric changes is found to be dependent on the level of the applied axial and lateral pressures.
- There is no simple linear relationship between the permeability and the volumetric change. The coal sample has different permeability behaviour that varies with volumetric changes.

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