PERMEABILITY OF INDIAN COAL

A REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology
In
Mining Engineering

By

NILABJENDU GHOSH

Department of Mining Engineering
National Institute of Technology
Rourkela-769008
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107MN028

Under the Guidance of
Dr. MANOJ KUMAR MISHRA

Department of Mining Engineering
National Institute of Technology
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Rourkela

CERTIFICATE

This is to certify that the thesis entitled "***PERMEABILITY OF INDIAN COAL***" submitted by Sri Nilabjendu Ghosh, Roll No. 107MN028 in partial fulfilment of the requirements for the award of Bachelor of Technology degree in Mining Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma

Date:

(Dr. MANOJ KUMAR MISHRA)
Associate Professor
Department of Mining Engineering
National Institute of Technology
Rourkela - 769008

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May 2011, Rourkela NILABJENDU GHOSH

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ABSTRACT

Now-a-days there is much constraint being faced by coal mine operators from multiple stake holders. Those are local inhabitants, environmental activists, government regulatory bodies, etc. It has focused attention to develop alternate approaches to extract coal resource. Coal bed methane drainage and carbon dioxide sequestration is one of such mechanism. Determination of the permeability of coal seams has a huge bearing on the identification and selection of viable sites for carbon sequestration. In this study an attempt was made to find out the permeability of coal from Ib Valley area of Mahanadi Coalfields Limited. Samples were collected from a local mine and cores were prepared according to standard procedures. An experimental setup was designed and fabricated based on the constant head method of permeability determination and tests were carried out on the samples for over a period of time. The results obtained were compared with values reported by others' and it was found that the setup gave a reasonable measure of the permeability of the sample.

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CHAPTER 1

INTRODUCTION

General Introduction

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1.1 GENERAL INTRODUCTION

Determination of coal rock properties (cleat porosity, permeability and gas-water relative permeability) is necessary for prediction of methane production rates in coalbed methane operations. Porosity in coal consists of matrix porosity (where the methane is adsorbed on the coal surface) and cleat porosity. It is the cleat network that provides the permeability for fluid flow in coal. For the calculation of coalbed methane content, gas content of the coal is taken to be equivalent to porosity in a conventional undisturbed gas reservoir.

Carbon sequestration in coal gas reservoirs, a technique to combat atmospheric CO_2 while simultaneously enhancing the recovery of CH_4, is a viable option in the immediate future. However, injected CO_2 in deep coal seams, while getting adsorbed, results in swelling of the solid coal matrix in addition to displacing additional methane. This, in turn, reduces the cleat aperture, and hence, the coal permeability. A significant reduction in permeability can hinder the flow of CO_2/CH_4 in the reservoir making this option of CO_2 sequestration economically unfeasible.

Among the various geological carbon sequestration options, permanent storage of CO_2 in coal seams is attractive due to their ability to enhance the recovery of coalbed methane (ECBM). The CO_2–ECBM technique involves injection of CO_2 in deep coals, where it gets preferentially adsorbed onto coal, thus displacing the naturally occurring methane gas. Injection of CO_2 improves the gas production rate and ultimate recovery of methane substantially.

1.2 BACKGROUND OF THE PROBLEM

Measurements carried out in Antarctic ice cores show that before industrial emissions started atmospheric CO_2 levels were about 280 parts per million by volume (ppmv), and stayed between 260 and 280 during the ten thousand years prior to that. Carbon dioxide concentrations in the atmosphere have gone up by approximately 35 percent since the 1900s, rising from a value of 280 parts per million by volume to 387 parts per million in 2009. Since the Industrial Revolution began, the concentrations of the greenhouse gases in the atmosphere have increased. For example, the concentration of carbon dioxide has increased by about 36% to 387 ppmv, or 100 ppmv over modern pre-industrial levels. The first 50 ppmv increase took place over 200 years, from the start of the Industrial Revolution to around 1973; however the next 50 ppmv increase took place in only 33 years, from 1973 to 2006. Recent statistics also shows that the concentration is increasing at a still higher rate. In the 1960s, the average annual rise was only 37% of what it was in 2000 through 2007.

Carbon sequestration is defined as the capture and storage of carbon dioxide that would otherwise be released into the atmosphere. The captured gases can be stored in deep geologic formations, dissolved in deep oceans, converted to rock-like solid materials, or absorbed by trees, grasses, soils and algae. Carbon sequestration is being seen as a viable mitigation strategy to help stabilize global CO_2 emissions and reduce the impacts of climate change. One of the options available regarding the selection of sequestration sites are deep unmineable coal seams. Coal seams that have never been disturbed can contain considerable amounts of methane (up to $25m^3$ per tonne of coal). This coal typically lies between 300 and 1500 m below the surface, with reserves of more than 4000 billion tonnes of coal at these depths. Typically 50% of the methane in the coal can be recovered using standard techniques. In the most favourable coal basins it is estimated that 15 GT of CO_2 could be stored in coal seams. In the best sites, the operating income from increased methane production would compensate for the additional costs associated with CO_2 injection. Far more CO_2 (perhaps 20 to 50 times as much) could be stored in less favourable coal basins, where costs would be higher. A key factor determining the attractiveness of a particular site is the permeability of the coal. This necessitates the study of the permeability of coals. There exists a very limited published document on the coal deposit of the area under investigation particularly on its permeability characteristics. So an attempt has been made to determine the permeability of the coal from the area.

1.3 OBJECTIVES

The aim of the present study is to determine the permeability characteristics of Indian coal.

1.3.1 Specific Objectives The above goal has been achieved by addressing the following specific tasks:

i. Critically understanding the behaviour of coal under different influences, conditions, particularly with reference to permeability through review of pertinent literature.
ii. Devising an experimental setup for permeability measurement.
iii. Determination of permeability of coal in laboratory.
iv. Comparison of results obtained from the test with others' reports.

1.4 METHODOLOGY

The flowchart shown in figure 1 depicts the plan of action undertaken for fulfilment of the above mentioned goals:

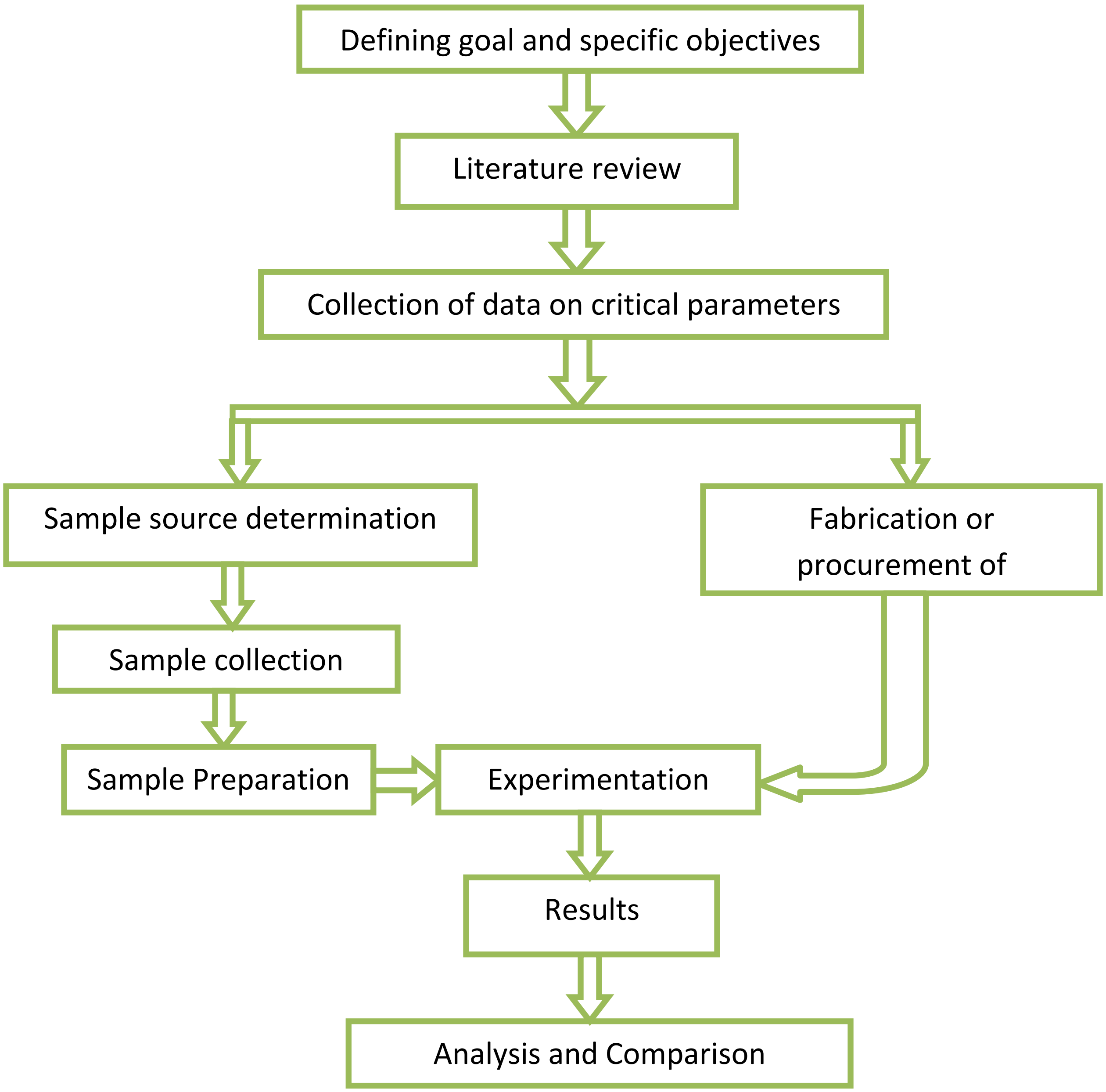

Fig 1: Flowchart depicting the steps involved in the process of project completion

CHAPTER 2

LITERATURE REVIEW

Basic Definitions

Direction of permeability

Permeability Determination

Review of Permeability Experiments

Causes of permeability reduction

2.1 BASIC DEFINITIONS

Permeability is one of the index properties of rock. Permeability is considered important in describing a rock because it conveys information about the degree of interconnection between the pores or fissures which are the basic parts of the rock framework. Furthermore, the variation of permeability with change in normal stress, especially as the sense of the stress is varied from compression to tension, evaluates the degree of fissuring of the rock, since flat cracks are greatly affected by normal stress whereas spherical pores are not. Also, the degree to which the permeability changes by changing the permeant from air to water expresses interaction between the water and the minerals or binder of the rock.

Most rocks obey Darcy's law.

$$q_x = k.\ A.\ dh/dx$$

where,

q_x is the flow rate (L^3T^{-1}) in the x direction.

h is the hydraulic head with dimension L.

A is the cross-sectional area normal to x (dimension L^2).

When temperature will vary considerably from 20°C or when other fluids are to be considered, a more useful form of Darcy's law is

$$q_x = (K/\mu).A.\ dp/dx$$

where,

p is the fluid pressure with dimensions of FL^{-2}.

μ is the viscosity of the permeant with dimensions $FL^{-2}T$.

K is the hydraulic permeability.

2.2 DIRECTION OF PERMEABILITY

It has been observed by **Gash et al (1992)** that the permeability is largest parallel to the bedding planes in the direction of the face cleat and at 1,000 psig confining pressure, permeability parallel to the bedding planes in the face cleat direction was 0.6-1.7 md and in the butt cleat direction, 0.3-1.0 md. The permeability was 0.007 md when calculated perpendicular to the bedding planes. Confining pressure (i.e., stress) has an influence on cleat porosity, permeability and hence, relative permeability. Increasing confining pressure from 450 psig to 1,000 psig with an injection pressure of 370 psig and a 70 psig pressure drop reduces the measured value of permeability by a factor of 5 in all cleat orientations. The cleat porosity is lowered by approximately a factor of 1.7 by the same pressure drop. Increasing confining pressure leads to an upsurge in the ratio of the gas relative permeability to the water relative permeability

The cleat structure suggests that permeability in coal should be anisotropic. The face cleat is usually better developed than the butt cleat. The less developed butt cleat is at right angles to the face cleat. Both types of cleats are perpendicular to the bedding planes. Theoretically speaking, permeability should be greatest parallel to the face cleat. Vertical permeability is supposed to be non-existent if the cleat structure does not extend through the bedding planes. The fractured nature of coal also means that the permeability will decrease as net confining pressure increases, closing the fractures in which fluid flow occur.

Absolute permeability to water in coal cores decreases with continued injection of water.

2.3 PERMEABILITY DETERMINATION

Permeability can be determined in the laboratory by measuring the time for a measured volume of fluid to pass through the concerned specimen when a constant air pressure acts over the surface of the fluid. An alternative method is to generate radial flow in a hollow cylindrical specimen which is prepared by drilling a coaxial central hole in a drill core. When the flow is from the outer circumference toward the center, a compressive body force is set up, whereas when the flow is from the central hole toward the outside, a tensile body force is generated. As a result, rocks that owe their permeability partly to the presence of a network of fissures demonstrate a profound difference in permeability values according to the direction of flow.

2.3.1 Constant Head Permeability Test

The constant head permeability test is carried out by initiating flow of water through a column of cylindrical rock sample under a constant pressure difference. The test is carried out in a permeability cell or a permeator, whose size varies with the grain size of the tested material.

The rock sample is cylindrical with its diameter being large enough in order to be representative of the tested rock. As a thumb rule, the ratio of the cell diameter to the largest grain size diameter should be higher than 12. The usual size of the cell which is used for testing common rocks is 75 mm in diameter and 260 mm in height between perforated plates. The testing apparatus is equipped with an adjustable constant head reservoir and an outlet reservoir which allows maintaining a constant head during the test. De-aired water used for testing at constant temperature. The permeability cell is also provided with a loading piston which allows us to apply constant axial stress to the sample while the test is being carried out.

Before starting the flow measurements, however, the sample is saturated. During the test, the amount of water that is coming out of the sample is measured at given intervals of time. Taking the height of the sample column as L, the sample cross section as A, and the constant pressure difference as Δh, the volume of passing water as Q, and the time interval as ΔT, the permeability of the sample can be calculated as

$$K= QL / (A.\Delta h.\Delta t)$$

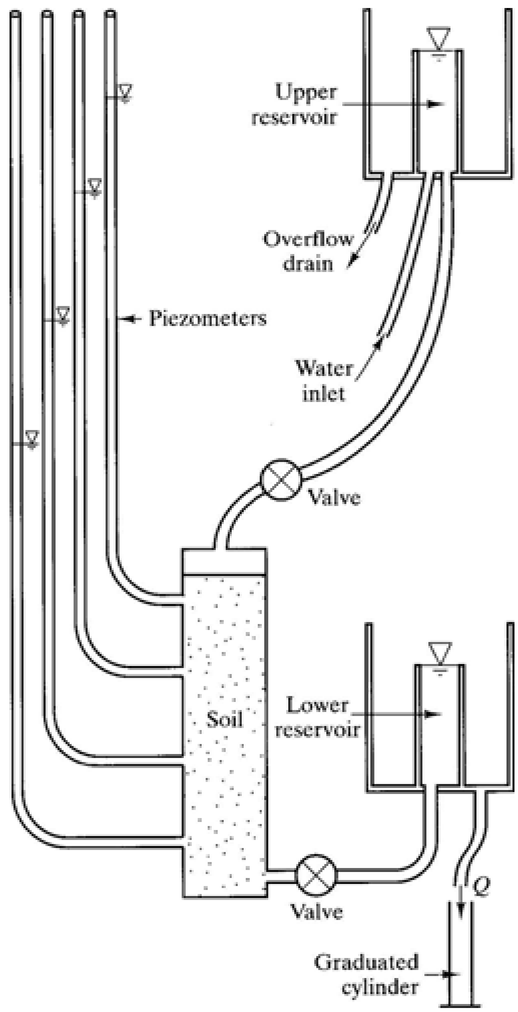

Fig 2: Schematic of a constant head permeameter (Coduto, 1999)

2.3.2 Falling Head Permeability Test

The falling head permeability test is undertaken by initiating flow of water through a relatively short rock sample connected to a standpipe which provides the water head and also allows measuring the volume of water passing through the sample possible. The diameter of the standpipe is determined depending on the permeability of the tested rock. The test can be carried out in a Falling Head permeability cell or as well as in an oedometer cell.

Before starting the flow measurements, the sample is saturated and the standpipes are filled with water which is previously de-aired to a given level. The test is initiated by allowing water to flow through the sample until a given lower limit is reached within the standpipe. The time required for the water in the standpipe to drop from the upper to the lower level is recorded. Most times, the standpipe is refilled and the test is repeated. The recorded time should be the same for each test or within an allowable variation of about 10% otherwise the test is considered as failed. The permeability of the sample can then be calculated as

$$K = [a.L / (A.\Delta t)].\mathrm{Log}\,(h_U / h_L)$$

where

L: the height of the sample column

A: the sample cross section

a: the cross section of the standpipe

Δt: the recorded time for the water column to flow though the sample

h_U and h_L : the upper and lower water level in the standpipe respectively

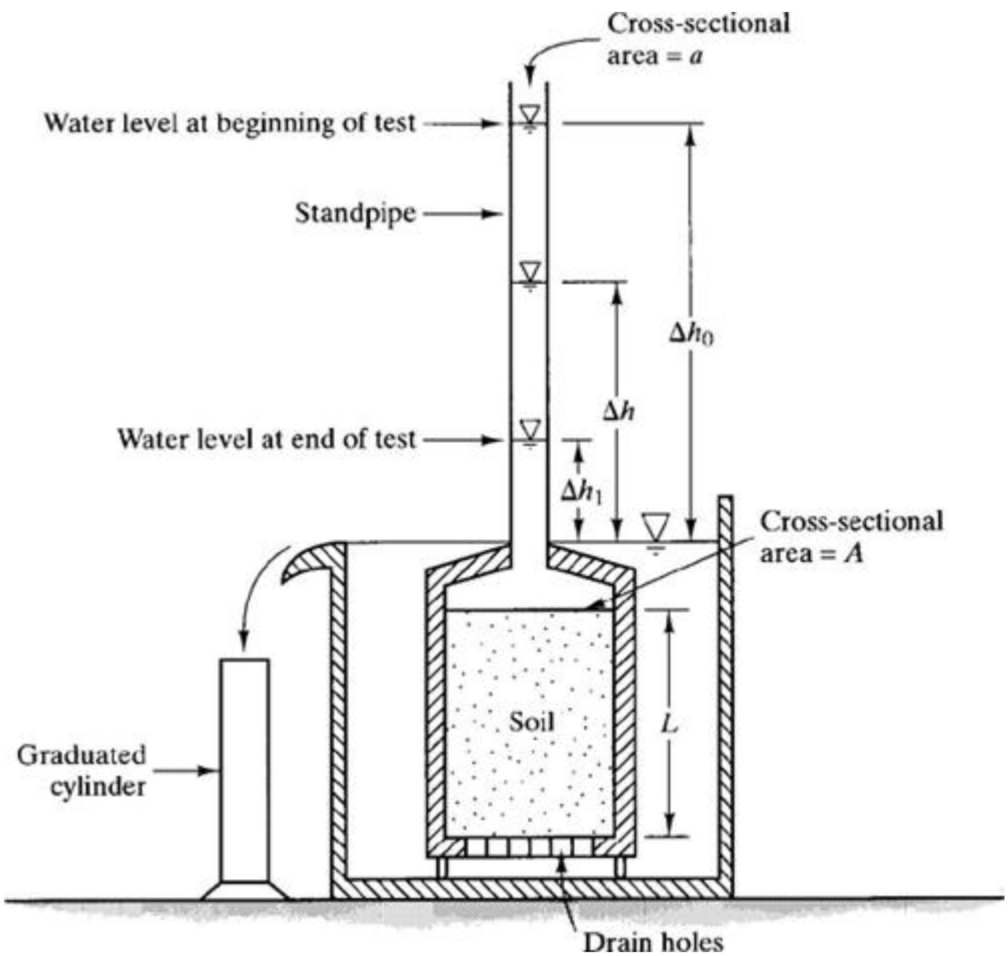

Fig 3: Schematic of a falling head permeameter (Coduto, 1999)

2.3 REVIEW OF PERMEABILITY EXPERIMENTS

2.4.1 SERVO-CONTROLLED TESTING SYSTEM

Wang and Park (2002) carried out experiments by making use of the Electro-Hydraulic Servo-controlled Rock Mechanics Testing System (MTS 815). The system was configured with a pulse-decay transient apparatus for performing the permeability test of rocks and concrete.

Before carrying out the tests, the specimen inserted into a plastic membrane jacket and placed into the chamber on the lower platen of the load frame. At the next step, the specimen was erected manually so as to slightly contact the upper platen with a load reading of 1–2 kN. The triaxial cell was lowered and filled with oil, and then the predetermined confining pressure was applied. In carrying out the tests, confining pressures of 4, 5, 6, 7 MPa were selected in reference to the mining depth.

At the beginning of the tests, they used the following conditions: the confining pressure was assumed constant; the pore pressure on the both upper and lower ends was taken to be equal. It should be noted that the confining pressure should be always higher than the pore pressure to prevent leakage. By decreasing the pore pressure to at one end of the specimen, a difference in the pore liquid pressure is applied, which allows the fluid to flow from one end of the specimen toward the other. In this study, the authors tested pore pressures of 3.8, 4.8, 5.8 and 6.8 MPa, with a variance of 1.5 MPa between the ends. The test machine, by the aid of closed loops, can control individually and accurately the axial loading, the confining pressure and the pore pressure. At each loading level, the axial stress and strain were kept constant as well as the pore pressure. In the process of the test, the axial stress, strain and permeability were recorded in time intervals of 20 s.

During the experiment, the rock specimen underwent different deformation stages, which can be chronologically listed as linear elastic deformation, elasto-plastic deformation, peak and post peak deformation. Thus, the relationship of permeability of the rocks with the stresses and deformation in a complete stress–strain process under triaxial compression were attained.

2.4.2 HIGH PRESSURE DEVICE AND PROCEDURE

Mazumdar and Wolf (2003) carried out experiments in a high pressure device and reported the following procedure: The high-pressure reactor in which the coal is placed for testing has a maximum annular isotropic pressure of 11 MPa. This isotropic stress is applied on an inner cylinder of synthetic rubber, which contains the specimen. The lengths of the sample or sample pieces are about 250 mm and the diameters are 72 mm. The size is such that there is presence of a representative cleat system in the sample. During the experiment, displacement transducers measure volumetric changes of the sample. A gas booster injects various gases and water into the coal at known rates and pressures. After leaving the coal, the produced fluid and gases are analyzed by a gas chromatograph, which gives the composition of the components. The experiments usually take two to six weeks to complete and provide information on sorption related permeabilities of the available cleat system.

The tests start with mounting a sample tube in the high-pressure reactor which is a complex procedure, followed by testing of the entire tubing system for leaks. The sample is connected with a vacuum pump, for at least 24 hours to 1 week, so that all gases and water or moisture are eliminated. Then the coal is filled with methane in cycles. After each injection cycle time is given for the methane to adsorb in the coal matrix until equilibrium is reached. In order to simulate sub-surface conditions, the difference between the annular pressure and the pore pressure is usually kept at ratios in between 2:1 up to 5:3. The injected methane is counted by a mass flow meter till the necessary pore pressure is arrived. Then, if needed, water is injected and both, the tubing system and the pump are brought to the same pressure and temperature conditions as the methane filled sample. More methane will adsorb and again time is needed for this methane to reach a new equilibrium pressure. At the same time the sample and vessel are brought to the desired temperature. In the following injection cycle the pump is filled with CO_2 and injection starts. The gas analyser determines the relative amount of methane, carbon dioxide and nitrogen (for annular leak detection) in the product gas. The water is separated and weight is measured. During the tests the recorded data serve as an iterative feedback in order to rule out their influence in the interpretation afterwards.

2.4.3 RIGID PERMEABILITY APPARATUS

Kuznetsov and Trofimov (2007) tested the permeability of coal in a rigid apparatus and reported, In the world practice, cylindrical cores are used to evaluate permeability of strong collectors. The cores are squeezed in special machines: by a hydraulic press, axially from ends and by a liquid, radially along the side surfaces. The cores of coal and weak materials easily fail under the said triaxial compression and appear unsuitable for the permeability assessment. In order to eliminate this situation, the triaxial compression should be rather rigid relative to normal displacements. This essentially diminishes strength defect manifestations and allows applying high stresses with no destruction. Thereupon, coal bulking and shrinkage due to the pressure-related variations of the sorbed gas quantities can basically take place owing to fracturing and porosity, which change permeability as well.

In the chamber, the core is compressed axially by a loading plate and radially by cone-shaped construction units pressed into the cavity by the same plate. The plate connects rigidly to the casing under the prescribed level of compression and, thus, rates the core strain.

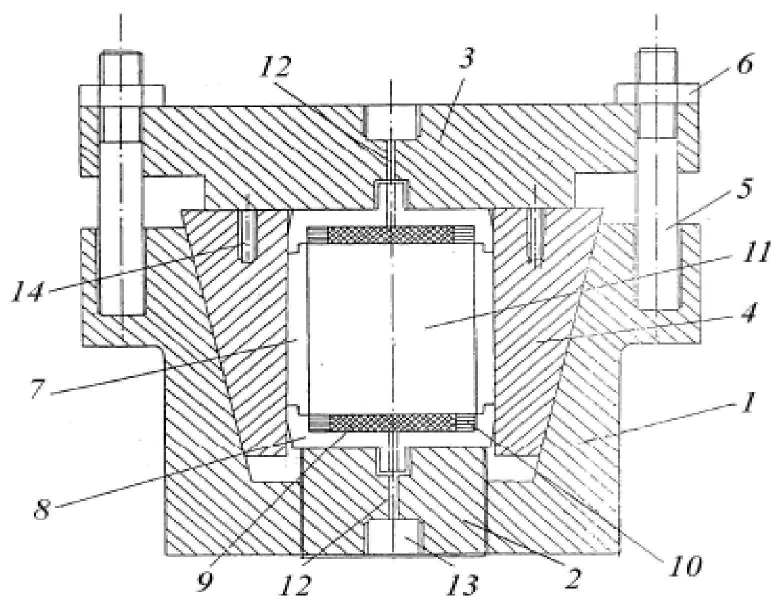

Fig 4: Schematic view of the rigid permeability apparatus (Kuznetsov and Trofimov, 2007)

(*1* — body of chamber with cone cavity; *2* — sliding bush in the chamber bottom; *3* — press plate; *4* — cone-shaped construction units; *5* — locking pins; *6* — screws; *7* — core casing; *8* — caps of core casing; *9* — rigid permeable gaskets; *10* — stop rings; *11* — core; *12* — gas inlet and outlet channels; *13* — nipple sockets for gas channels; *14* — disassembly sockets)

2.4.4 MATRIX SWELLING/SHRINKAGE EXPERIMENTS

Harpalani and Mitra (2008) carried out experiments on matrix swelling/shrinkage on coals from Illinois and San Juan and reported, The setup for measurement of matrix shrinkage/swelling and incremental swelling consisted of high-pressure vessels, a gas chromatograph to measure the molar gas composition at equilibrium, a pressure monitoring and recording system for each vessel, and a data acquisition system (DAS) to measure and record sorption-induced strain. In order to ensure that the temperature over the entire duration of the experiment remained constant, the high-pressure vessels were kept in a large constant-temperature bath.

The investigators have reported, "Each sample was first subjected to increasing helium pressure. Since helium is an inert gas, the measured volumetric strain was purely related to mechanical compression of solid coal resulting from changes in the external pressure. The volumetric strain found out was used to calculate the matrix (or grain) compressibility of the samples. After completing the helium tests, helium was bled out from the sample containers. Two samples were then subjected to stepwise flooding with methane and one with CO_2. Gas pressure in the sample containers was increased in steps of ∼1.38 MPa to the final pressure, which was 5.5 MPa for Illinois core and 6.9 MPa for the San Juan core. Gas injection for each incremental pressure step was performed only after attaining strain equilibrium following the previous step. Following this initial experimental phase, two samples were completely saturated with methane and one with CO_2."

One of the methane-saturated samples was then selected to replicate the CO_2–ECBM process (CO_2 injection). For this, methane was gradually replaced by CO_2, keeping the total gas pressure constant. Again, the "gas switching," that is, decrease in methane concentration and simultaneous increase in CO_2 concentration, was performed by stepwise injection of CO_2. At the end of each step and prior to injection (i.e., after attaining strain equilibrium for a pressure step), a sample of gas mixture was taken and analyzed using a gas chromatograph (GC) to determine the concentrations of methane and CO_2. Using the measured gas concentrations, partial pressures of the two gases were calculated. The procedure was continued until the gas, within and surrounding the sample, was pure CO_2.

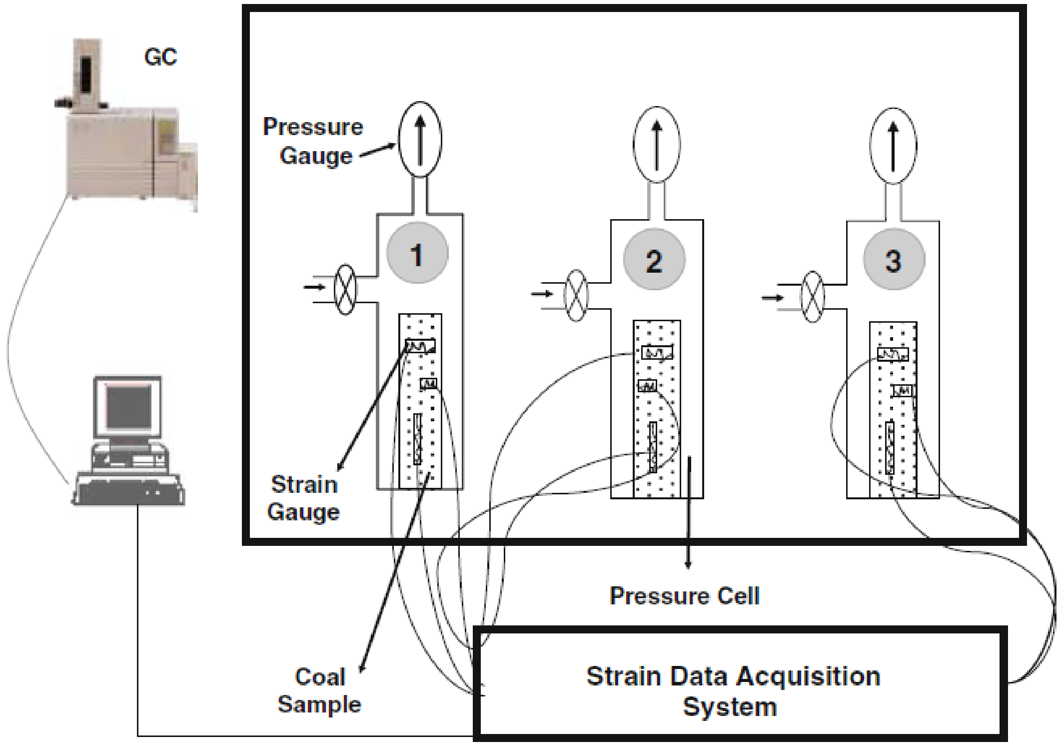

Fig 5: Experimental setup for measuring coal matrix shrinkage/swelling (Harpalani and Mitra, 2008)

2.4.5 PERMEABILITY EXPERIMENTS

Harpalani and Mitra (2008) tested coals with helium gas as the permeant and reported the following procedure: Sample core of 5 cm diameter and 7.5-10 cm length were used. The two end surfaces of each specimen were polished to enable proper placement in the triaxial cell. In order to replicate in situ conditions, where lateral confinement does not allow horizontal strain, it is imperative that the experimental setup allows external stress conditions and gas pressures to be monitored and controlled. Hence, the experimental setup for permeability measurement included independent control of axial and confining stresses, gas pressure (upstream and downstream), and measurement of gas flow rate. This experimental setup can be used to produce a zero horizontal strain scenario, that is, the core is not permitted to physically expand/shrink. Instead, the horizontal stress is adjusted when the sample begins to swell/shrink. The setup consisted of a triaxial cell, a circumferential extensometer to monitor and control the shrinkage and swelling of core, a loading system, and a means to monitor and measure flow rate. The temperature of the entire setup was kept constant using heating tape and temperature controller for the cell and water baths for gas circuits at the inlet and outlet.

The aforementioned authors have reported the following, "Core from the Illinois Basin was taken from a depth of 268 m, where gas pressures were estimated to have been ∼2.76MPa and reservoir temperatures 22°C. After attaining stress equilibrium following triaxial loading, the core would be saturated with methane at the desired pressure. The circumferential strain would then be set to zero. From this point on, no horizontal strain was to be allowed during the experiment and swelling/shrinkage due to switching of gases was to be prevented by varying the confining stress appropriately. After attaining equilibrium, the flow rate would be measured by applying a pressure gradient of 0.27–0.41MPa to calculate the core permeability."

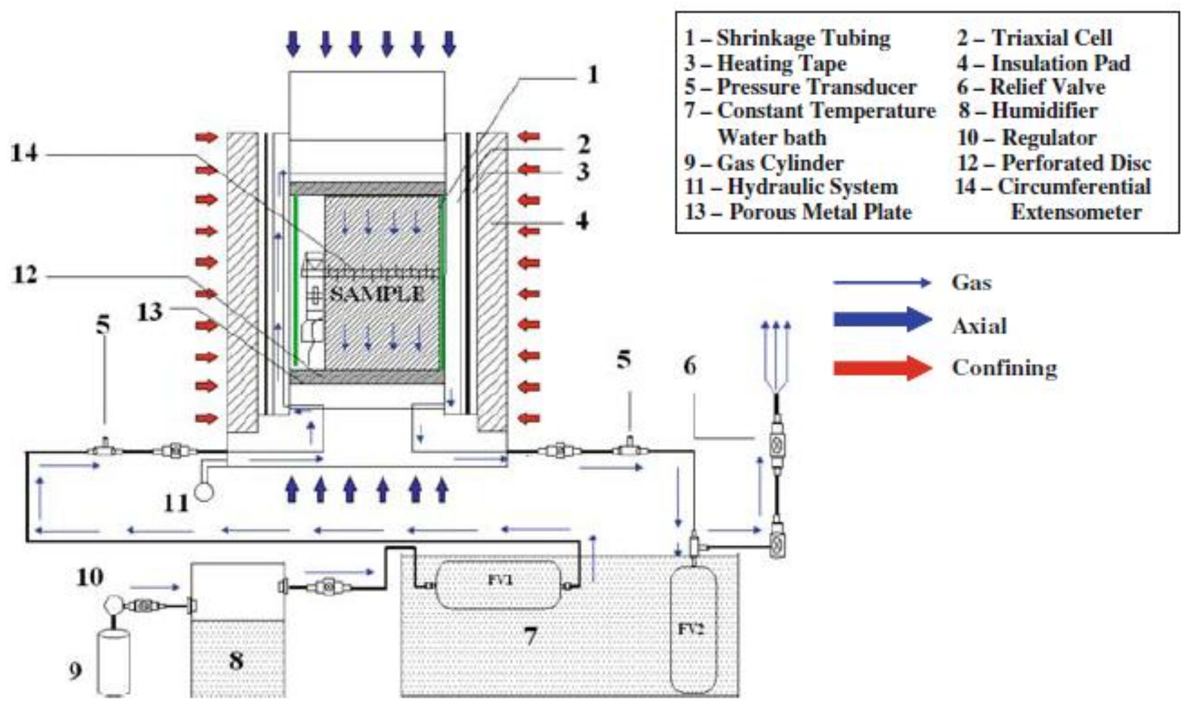

Fig 6: Schematic diagram of the Permeability setup (Harpalani and Mitra, 2008)

2.5 CAUSES OF PERMEABILITY REDUCTION

During the permeability measurements several diagnostic techniques were employed by **Gash et al. (1992)** to determine the cause of the permeability decline and to stabilize it. These included:

(1) Use of 0.2 m NaCl and 0.2 m KCl solutions in place of distilled water. Coals having low ash content (7% on a dry basis) use of 0.2 m NaCl and 0.2 m KCl had little effect compared to distilled water.

(2) Injection fluids were sterilized to eliminate bacterial growth and carefully filtered. This had no effect on the permeability values.

(3) Flow of fluid in the cores was reversed. Reversal of flow increased the permeability temporarily but did not have any significant effect on the final outcome.

(4) Cores were removed and refaced. Refacing of the cores increased the permeability temporarily but did not have any significant effect on the final outcome.

(5) Injection was stopped while confining pressure was maintained for approximately one month. In this case the permeability did not decline during the period injection was stopped.

There are probably a number of causes for permeability decline in coal cores, any one of which can be the dominant factor in a particular core depending on ash content and friability. The flow reversal results indicate fines migration plays a role in coal permeability decline, which may be generated in facing a coal core.

Even with the complications of permeability reduction, it is apparent that permeability in coal is a function of flow orientation as expected from the fractured nature of coal. The permeability is greatest with fluid flow parallel to the bedding planes and parallel to the face cleat orientation. Permeability is lowest perpendicular to the bedding planes. The permeability parallel to the butt cleat is about half that in the face cleat direction. Permeability measurements in coal should be made parallel to the bedding plane, just as in conventional reservoir rock. They conclusions has been summarised below:

1. There is no effect of cleat orientation on gas-water relative permeability in well-cleated coal cores.

2. Permeability is largest in the face cleat direction. The permeability measurements parallel to the bedding planes are comparable to those calculated from reservoir pressure transient analysis and required for history matching of coalbed methane production. In general, laboratory permeability measurements made perpendicular to the bedding planes in coal are much lower than the values used in simulation studies.

3. Confining pressure (i.e., stress) has an effect on cleat porosity, permeability and relative permeability. Increasing confining pressure decreases the flow of gas (relative permeability to gas) less than it does the flow of water (relative permeability to water).

2.5.1 Carbon Sequestration in coal seams

Coal seams provide an excellent target for CO_2 sequestration due to the ability of coal to physically adsorb large volumes of CO_2, the ease of availability of deep coalbeds throughout the world, and their proximity to power plants which are regarded as the main source of CO_2 emissions. Also, a considerable amount of knowledge has been acquired, technology and models developed in the area of coalbed methane recovery; all of which can be easily adapted to CO_2 flow and storage. Thus the concept of CO_2 sequestration, coupled with enhancement of coalbed methane recovery to serve as an incremental energy source, is considered to provide good long-term benefits, both environmental and economical. However, injected CO_2 in deep coals not only displaces additional methane while getting adsorbed, but also results in swelling of the solid coal matrix associated with adsorption. This, in turn, reduces the cleat aperture, and hence, the coal permeability. A significant reduction in permeability can hinder the flow of CO_2/CH_4 in the reservoir making this option of CO_2 sequestration economically unfeasible.

2.5.2 Effect of Matrix Shrinkage/Swelling in CO_2-ECBM

The CO_2–ECBM technique involves injection of CO_2 in deep coals, where it gets preferentially adsorbed onto coal, thus displacing the naturally occurring methane gas. Injection of CO_2 improves the gas production rate and ultimate recovery of methane substantially. However, in a typical CBM operation, the permeability of coal increases dramatically with desorption of methane, as a result of matrix shrinkage and opening up of cleats. In an ECBM operation, the simultaneous desorption of methane and adsorption of CO_2 results in an overall increase in the volume of sorbed gas and thus “swelling” of the matrix, resulting in cleat closure and reduction in coal permeability.

Field observations and available data show a dramatic reduction in the permeability of coal as a result of CO_2 injection. With CO_2 injection, there is an increase in methane recovery of over 130%. This increase in recovery is primarily due to displacement of methane by CO_2. After 2000 days of continuous CO_2 injection, the amount of CO_2 sequestered is more than four times the additional methane produced.

CHAPTER 3

EXPERIMENT AND METHODS

ASTM Standard

Experiment Design

Description of the mine

3.1 ASTM STANDARD

The American Society for Testing and Materials gives an overview of the constant head method for determination of permeabilities of rocks in standard number ASTM D4630 - 96(2008). Below is a short description of the method.

Significance and Use

Test Method - The constant pressure injection test method is used to define the transmissivity and storativity of low-permeability formations adjacent to packed-off intervals. Advantages of the method are: (1) it avoids the effect of well-bore storage, (2) it may be utilized over a wide range of rock mass permeabilities, and (3) it is significantly shorter in duration than the orthodox pump and slug tests used in more permeable rocks.

Analysis - The transient water flow rate data obtained using the recommended test method are calculated by the curve-matching technique described by Jacob and Lohman and extended to investigation of single fractures by Doe et al. If the water flow rate reaches steady state, it may be employed to determine the transmissivity of the test interval.

Units

Conversions - The permeability of a formation is often expressed in terms of the unit darcy. A porous medium has a permeability of 1 darcy when a fluid of viscosity 1 cp (1 mPa·s) flows through it at a rate of 1 cm^3/s ($10{-}6\ m^3/s$)/1 cm^2 ($10{-}4\ m^2$) cross-sectional area at a pressure differential of 1 atm (101.4 kPa)/1 cm (10 mm) of length. One darcy corresponds to 0.987 μm^2. For water as the flowing fluid at 20°C, a hydraulic conductivity of 9.66 μm/s corresponds to a permeability of 1 darcy.

1. Scope

1.1 This test method covers a field technique for determining the transmissivity and storativity of geological formations having permeabilities lower than $10^{-3}\ \mu m^2$ (1 millidarcy) using constant head injection.

1.2 The transmissivity and storativity values ascertained by this test method provide a good approximation of the capability of the zone of interest to transmit water, if the test intervals are representative of the entire zone and the adjoining rock is fully water-saturated.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

3.2 EXPERIMENT DESIGN

Due to the permeability apparatus in the laboratory being out of service, an alternate experimental setup was devised. The schematic layout of such a fabrication has been shown in the figure 7.

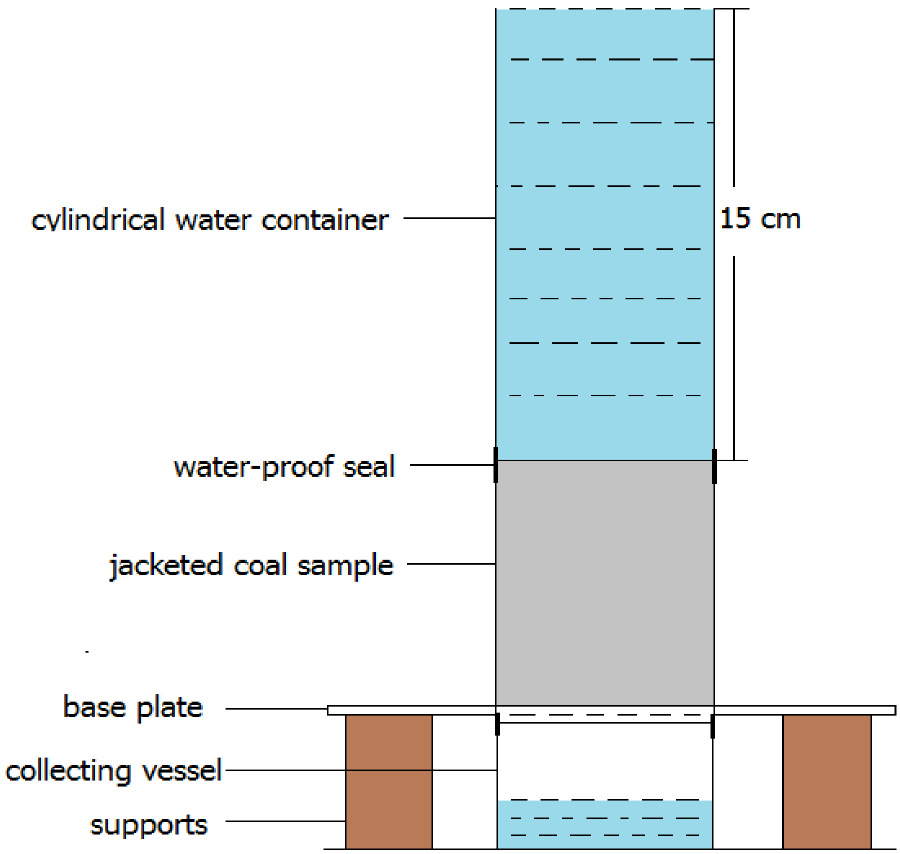

Fig 7: Schematic diagram of the experimental setup

Some salient features of the setup are as follows:-

1. The designed experimental setup is an unsophisticated version of the constant head method where a constant water head of 15 cm is maintained above the sample and the pressure acting over the surfaces of both the water head and the column of collected water is kept the same.
2. A cylindrical container for water was made out of transparent/translucent material which has a diameter such that the sample core of 5.4 cm diameter (along with a jacket of impermeable material) fits the cylinder snugly without any leakage.
3. The sample itself is first covered by an impermeable jacket so that fluid flow in the horizontal direction is prohibited.
4. To prevent leakage of water through the spaces between the cylindrical container and the sample, water-proof seals were used to plug these spaces.
5. A plywood base plate was made by making a circular hole whose diameter exactly matches that of the sample diameter, so that the plate can support the sample without impeding the flow of water through it.
6. A collecting vessel was kept under the setup to collect water flowing out of the sample and this vessel was connected to the bottom of the sample with flexible impermeable material to prevent external atmosphere from affecting the pressure on the surface of the collected water.
7. Water was poured into the cylindrical container so that the bottom of the body of water was in contact with the sample and a 15 cm head (as proposed by ASTM Committee D-18) above the sample was maintained by continual addition of water into the container.
8. Water coming out of the sample at the other end was collected in the above-mentioned collecting vessel. The height of the water in the collecting vessel was monitored continuously and measurements were carried out at intervals of 24 hours.
9. To accurately measure very small changes in the height of the collected water a scale was created in Adobe Photoshop with graduation of the order of 0.5 mm. The same was used to measure the collected water which had first been transferred into a measuring flask.
10. To get an idea of the variation of permeability according to the direction, one sample was cored perpendicular to the stratification whereas the other was cored parallel to the stratification. The heights of both samples were 8 cm.

One drawback of the adopted test method is that the volume of water in the outlet is dependent on the surface area of the sample, as the pressure of water acting over the sample is indirectly proportional to the diameter (and hence the surface area) of the sample.

Fig 8: Photograph of the experimental setup

3.3 DESCRIPTION OF THE MINE

Location

Sample collection was done from a local underground coal mine located in the district of Jharsuguda, Odisha. Located in the eastern part of India, this region has extensive reserves of Gondwana coal. The area can be approached by rail as well as road. The nearest town is Brajarajnagar. The State Highway (Jharsuguda-Raigarh) passes at a distance of 3.5 km from the mine.

Topography and Drainage

- The area is characterised by plain land gently sloping towards the east.
- The highest and lowest elevations of the area are 294 m and 230 m above mean sea level.
- The drainage of the area is mainly controlled by the Ib river which flows from north to south.

- The drainage is controlled by the Ib river through a number of ephemeral streams flowing in the area.

Geology

- The name of the seam is Lajkura.
- Lajkura seam no. 1, 2 and 4 are workable.
- Grade of the coal is D.
- The balance extractable reserves are 29.68 MT.
- The thickness of the seam is 18 to 20 m.
- The gradient of the seam is 1:10.5.
- Depth of cover is 20 m to 282 m.
- Dip direction: South 70^o West.

Present status of the mine

The Lajkura Seam-1 is extensively developed with LHDs. The Lajkura Seam-II is presently working through incline No.4 and 5. At present about 1700 tpd coal is being produced from Bord & Pillar development district with 8 LHDs. The Lajkura Seam-3 & 4 is almost virgin.

Coal winning and transportation

The mine is producing coal by solid blasting. Coal from the face is loaded by LHDs on to the belt conveyor which transfers coal to the gate belt conveyor. The gate belt conveyor transport coal out of district and load onto the trunk belt conveyor installed in the main dip. The trunk belt conveyor unloads the coal to belt conveyor which goes to surface bunker. From the surface bunker, coal is loaded into trucks (18t capacity) and transported to the railway siding, which is at distance about 2 km from the project.

Hydrogeology

- Sandstone between Lajkura and Parkhani seams form an aquifer depth of which ranges between 30 to 150 mbgl. The aquifer is semi-confined to confined in nature. Disintegrated formation above Parkhani seam or sandstone formation above Lajkura seam upto the land surface with a semi-pervious layer of limited thickness at a depth of 25 to 30 mbgl are encountered. The nature of aquifer is unconfined.

- The general movement of ground water in the ground water table aquifer is from north-west to south-east direction.
- The ground water level in this area ranges from less than 1.30 mbgl to about 4.20 mbgl in post-monsoon and less than 2.80 mgbl to about 7.62 mbgl in pre-monsoon period.
- The water level fluctuation annually varies from 1.64 m to 12.05 m in this area.

CHAPTER 4

RESULTS & ANALYSIS

Sample Collection and Preparation

Results

Analysis

4.1 SAMPLE COLLECTION AND PREPARATION

The coal sample for the present study was collected from a local underground colliery located in Jharsuguda district of Odisha. Field visits were made to collect the sample and other data. Discussions with mine officials were held to learn about the geology, specific problem, etc. Surface topography was also inspected. Fresh samples immediately after blasting were collected from a depth of 93 m for the analysis. The sample blocks were placed in gunny bags, sealed and finally placed in plastic bags so as to keep them unaffected by atmospheric factors. The bags were then placed in transportation boxes made of wood so that the samples were not affected by the transportation.

Sample cores both perpendicular and parallel to the stratification were obtained as per standard established procedures. The cores were cut with hacksaws and finally polished with corundum powder so that the flat surfaces were perpendicular to the curved surfaces of the cylindrical cores. Ultimately, the cores obtained had the following dimensions,

Diameter = 5.4 cm and Length = 8 cm

Fig 9: Photograph of the coring machine

Water was added to the sample while sampling to take off some of the heat produced while coring. After coring the samples were kept in the open to allow the superficial moisture to evaporate. This, however would not in any way, affect the inherent moisture content of the sample. Figure 9 shows the coring machine employed for the purpose of sample preparation and figure 10 shows the specimen preparation.

Fig 10: Coring being done

Fig 11: Finished sample (after polishing)

4.2 RESULTS

The height of the outlet water level was measured in a measuring flask (2.8 cm diameter) for 15 days and the daily variation of the same is tabulated below:

Table 1: Variation of outlet water height (sample parallel to stratification) with time

Time (day)	Height of water in outlet (cm)	Cumulative height (cm)	Flowrate (cm^3)	Relative flowrate (q_t / q_0)
1	2.15	2.15	13.238 (q_0)	1
2	1.45	3.60	8.928	0.674
3	0.85	4.45	5.234	0.395
4	0.75	5.20	4.618	0.348
5	0.75	5.95	4.618	0.348
6	0.60	6.55	3.694	0.279
7	0.45	7.00	2.771	0.209
8	0.30	7.30	1.847	0.139
9	0.25	7.55	1.539	0.116
10	0.20	7.75	1.232	0.093
11	0.15	7.90	0.924	0.069
12	0.10	8.00	0.616	0.046
13	0.10	8.10	0.616	0.046
14	0.05	8.15	0.308	0.023
15	0.05	8.20	0.308	0.023

Table 2: Variation of outlet water height (sample perpendicular to stratification) with time

Time (day)	**Height of water in outlet (cm)**	**Cumulative height (cm)**	**Flowrate (cm^3)**	**Relative flowrate (q_t / q_0)**
1	0.40	0.40	2.463 (q_0)	1
2	0.35	0.75	2.155	0.875
3	0.30	1.05	1.847	0.749
4	0.20	1.25	1.232	0.500
5	0.20	1.45	1.232	0.500
6	0.15	1.60	0.924	0.375
7	0.15	1.75	0.924	0.375
8	0.10	1.85	0.616	0.250
9	0.10	1.95	0.616	0.250
10	0.05	2.05	0.308	0.125
11	0.05	2.10	0.308	0.125
12	0.05	2.15	0.308	0.125
13	0.05	2.20	0.308	0.125
14	0.05	2.25	0.308	0.125
15	0.00	2.25	0	0

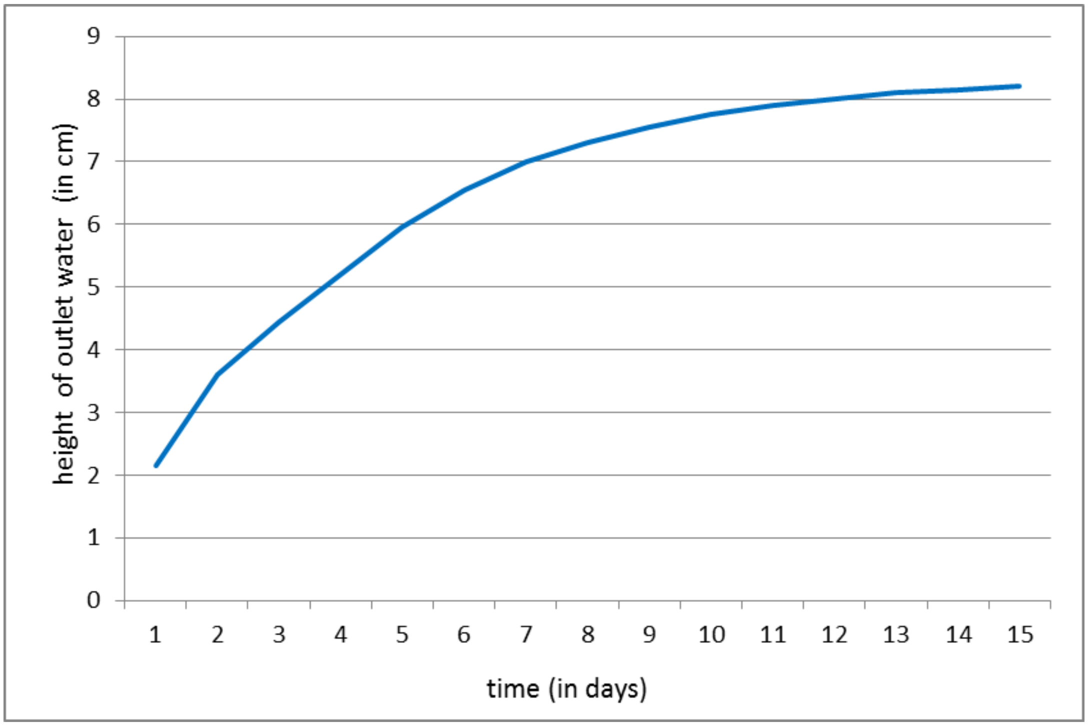

Fig 12: Graph showing the progressive variation of level of outlet water with time (sample cored parallel to stratification)

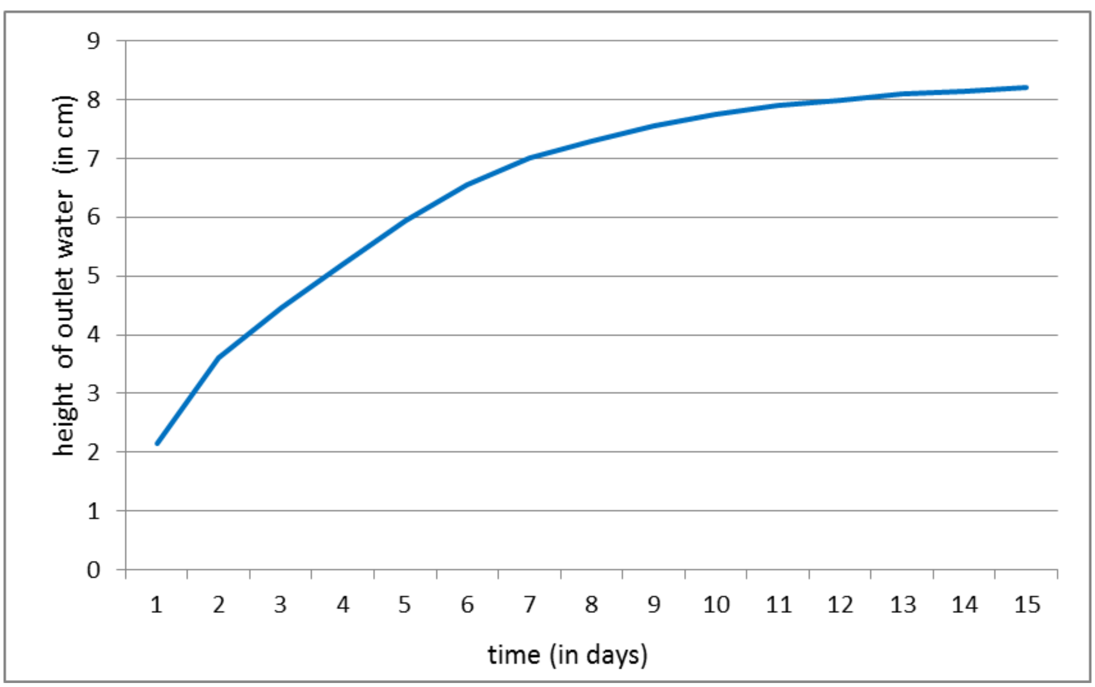

Fig 13: Graph showing the progressive variation of level of outlet water with time (sample cored perpendicular to stratification)

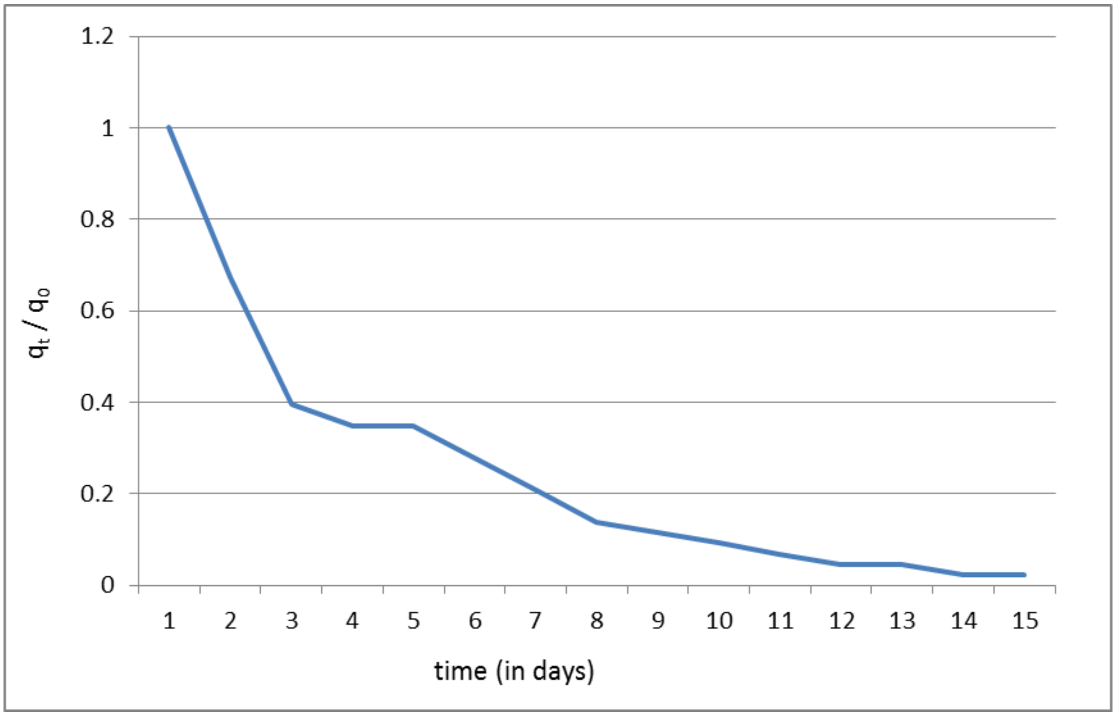

Fig 14: Graph showing the variation of relative flowrate with time (sample cored parallel to stratification)

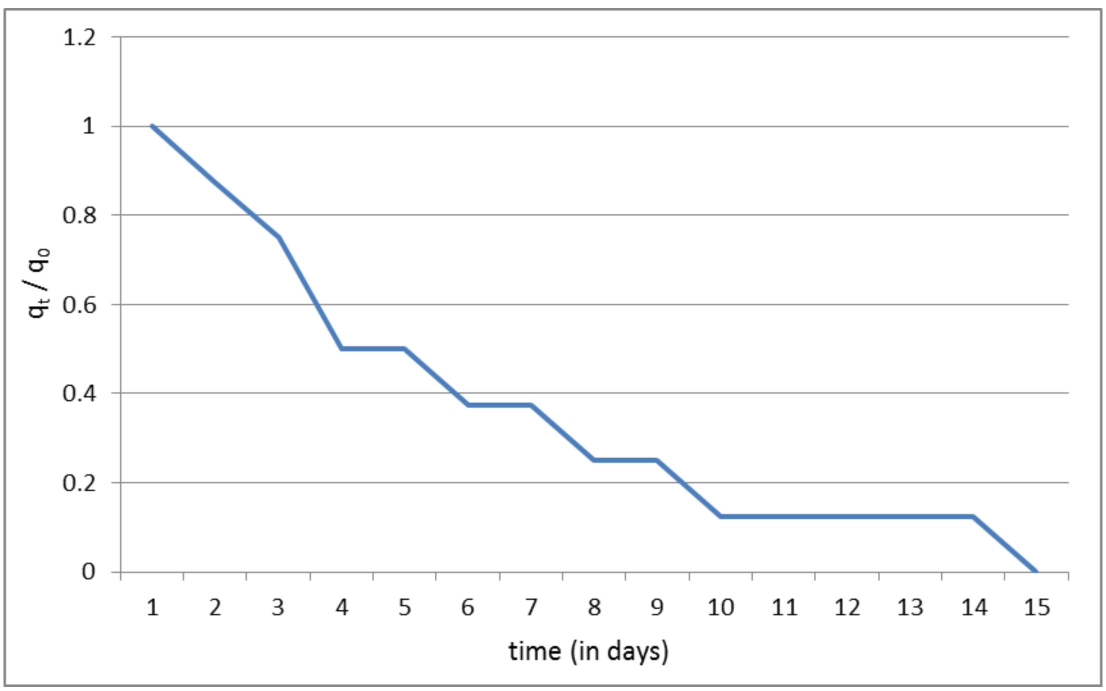

Fig 15: Graph showing the variation of relative flowrate with time (sample cored perpendicular to stratification)

4.3 ANALYSIS

As the measurement of outlet water was done in a measuring flask, the height in a collecting vessel with diameter equal to that of the sample has to be calculated by equating the corresponding volumes. This gives the head of the outlet water to be used in formula.

Accordingly the height of outlet water for

Sample cored parallel to stratification= 2.2 cm

Sample cored perpendicular to stratification= 0.6 cm

From the constant head method the permeability of the sample can be calculated as

$$K = QL / (A.\Delta h.\Delta t)$$

Where,

L= height of the sample column

A= sample cross section

Δh= head difference between inlet and outlet

Q= volume of passing water

ΔT= time interval

Using the above formula in the case of the sample cored parallel to the stratification, we get

L= 8 cm

A= $\pi * 2.7^2$ cm^2

Δh= (15 - 2.2) cm

Q= 55 cm^3

ΔT= 15 days= 15 / (3600*24*15) seconds

Hence coefficient of permeability, $K_{parallel}$= $1.158 * 10^{-6}$ cm s^{-1}

And in the case of the sample cored perpendicular to the stratification, we get

L= 8 cm

A= $\pi * 2.7^2$ cm^2

Δh= (15 – 0.6) cm

Q= 18 cm^3

ΔT= 15 days= 15 / (3600*24*15) seconds

Hence coefficient of permeability, $K_{perpendicular}$= $3.369 * 10^{-7}$ cm s^{-1}

From the above is found that the permeability of the coal sample in the direction parallel to the stratification is much more (about 10 times) than that in the direction perpendicular to the stratification.

Coefficient of permeability (average) of the coal sample= $1.7424 * 10^{-7}$ cm s^{-1}

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Recommendations

5.1 CONCLUSIONS

1. The grade of the coal is D. It was formed in the Upper Permian period and belongs to Gondwana coal.
2. Overall, the coefficient of permeability of the coal was found to be quite low with the minimum value being $3.369 * 10^{-7}$ cm s^{-1} and maximum being $1.158 * 10^{-6}$ cm s^{-1}.
3. Permeability parallel to the stratification was found to be greater than that perpendicular to the stratification. This can be attributed to the presence of a system of cleats within the coal matrix aligned parallel to the stratification.
4. The determined permeability value compares well with values reported by others (viz., Gash et al., 1992).

5.2 RECOMMENDATIONS

The samples tested in the present study were collected from the same depth. So, future study in this regard can be carried out on samples collected from different depths.

Also samples from different collieries can be tested and the variation in their permeabilities can be found out.

Tests may be carried out in a standard set up to measure the error percentage.

The tests for this study were carried out indoors. In the future, in situ tests can be carried out and from the difference in results between the two, the effect of in situ stresses on permeability values can be found out.

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