Radial Flow Permeability Testing of Indiana Limestone

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This paper presents the results of a series of laboratory bench-scale tests that have been conducted to determine the permeability characteristics of Indiana Limestone. The paper describes the experimental facilities, the test procedures and the results of the steady state flow experiments that are used to estimate the permeability of the rock.

1 INTRODUCTION

The geotechnical importance of studying fluid flow through porous media and soils in particular, becomes evident when dealing with groundwater movement in surficial geomaterials that can be initiated by hydraulic gradients that develop during construction activity, groundwater extraction, impounding of reservoirs and groundwater recharge during adverse climatic events. In a geotechnical context, rocks are regarded as virtually impermeable materials, with comparatively greater resistance to flow of water through their pore structure. The importance of the permeability of rocks comes to the forefront when deep geologic formations are used in geoenvironmental activities for disposal of hazardous and toxic materials. The permeability of the rocks encountered is of critical importance to these geoenvironmental activities since the movement or transport of the hazardous materials during their eventual release will be largely governed by the permeability characteristics of the geologic formation. The estimation of the permeability characteristic of geologic formations is a non-trivial exercise since the measure of permeability can be influenced by the scale at which the measurement is made. Regional-scale and borehole-scale estimates of the permeability can be greatly influenced by the inhomogeneities, including fractures, fissures, solution channels and other anomalies that are present in naturally occurring geologic media. These anomalies are considered to be site specific and can only be determined in a reliable fashion by either conducting tests at the appropriate scale or in the regional-scale through inverse analysis of tracer movement patterns in rock masses. The estimation of the permeability of intact units of a geologic medium has important geoenvironmental applications in connection with storage of wastes since the units in which repositories will be located should be sparsely fractured and the sealing of the fractures and fissures are a prerequisite to developing an efficient solution for storage. The intact permeability of geomaterials is therefore regarded as an important property that influences efficiency and reliability of geoenvironmental solutions for deep geologic disposal. The permeability of geomaterials such as concrete and cementitious grouts are also important to many geoenvironmental and infrastructure applications where durability of structural materials in general and cements used for sealing deep boreholes and other access shafts employed in waste management endeavours is influenced by the permeability characteristics of these materials.

The in situ measurement of permeability characteristics of intact rocks has been in existence since construction of concrete dams founded on rock (Mayer, 1963; Stagg and Zienkiewicz, 1968; Jaeger, 1972). The laboratory measurement of the permeability of relatively low perme-

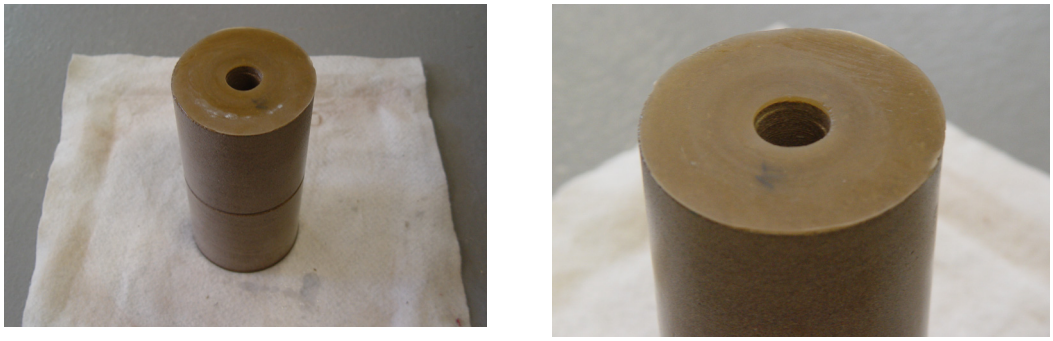
ability geomaterials, including rocks and concrete, has been the subject of extensive research over the past four decades with notable early work by Bernaix (1966), Habib and Vouille (1966), Londe and Sabarly (1966) and Brace et al. (1968). The testing methods include both steady state flow and pressure transient techniques conducted on cylindrical cores of rock. Reviews of the experimental techniques can be found in the articles by Selvadurai and Carnaffan (1997), Selvadurai et al. (2005) and Selvadurai (2009). The various advantages and disadvantages of the two basic approaches are fully discussed in these articles. Ideally, the simplest technique for determining the permeability of intact rock involves the attainment of steady state flow conditions in a sample, which is both easy to perform and easy to analyse theoretically, so that the permeability of the material can be conveniently estimated. The primary advantage of a steady state flow test is that the permeability can be estimated from knowledge of the hydraulic gradients applied to the sample, the established flow rate and the dimensions of the flow domain. These are quantities that can be measured relatively conveniently in most experimental situations. In transient tests on the other hand, in addition to the above data, information should also be available on the compressibility of the pore fluid and porous fabric as well as the porosity of the medium. Unless these parameters can be determined *a priori*, the accurate interpretation of the transient permeability tests is not feasible. The primary advantage of the transient test is that it can be performed relatively quickly whereas the steady state tests require time to establish a steady state. The choice of the most appropriate type of test ultimately depends on the type of material that is being examined. Transient tests are advocated for rocks such as granite (also cement grout) that has relatively low permeability (Brace et al. 1968; Selvadurai and Carnaffan, 1997; Selvadurai et al. 2005) and the steady state tests have been used for determining the permeability of materials with a comparatively high permeability, including sandstone and Indiana Limestone, the rock type used in this research (Selvadurai and Selvadurai, 2007; Selvadurai and Głowacki, 2008).

This research program examines the use of a radial flow steady state test to determine the permeability of Indiana Limestone. The steady state radial flow test has been used by many other investigators to determine the permeability characteristics of both limestone and sandstone and reference to these investigations are also given in the literature cited previously. The paper discusses the experimental procedures and presents the results of radial flow tests performed on two cylindrical samples of Indiana Limestone measuring 100 mm in diameter, 200 mm in length and containing a cylindrical cavity of diameter 23 mm. A further objective of the experimental investigations is also to determine the permeability of disc-shaped fractures introduced in the cylindrical sample and subjected to stresses normal to its plane. The correct interpretation of the fracture permeability requires a prior knowledge of the permeability of the intact Indiana Limestone, which will be provided by the initial phase of the research.

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1 *Sample preparation*

Six cylindrical samples of Indiana limestone were cored from a single block. The plane ends and cylindrical surfaces of each sample were ground to a smooth finish. The dimensions of the prepared cylinders were 100mm diameter by 200mm length. A cylindrical central cavity of diameter 20 mm was first drilled in the sample. Since the flow is initiated from the central cavity, it is essential that the inner cavity is free of debris that would have accumulated during the drilling of the central cavity. To avoid the influence of the debris clogging the surface pores of the central cavity, the drilled cavity is further bored to a final diameter of 23 mm. The upper and lower plane faces of the samples were epoxy coated to a thickness of 1 mm. The excess epoxy covering the central cavity was drilled to expose the internal cavity. The internal cavity was inspected for any debris, which was removed to prepare the sample for testing. Finally, a groove was machined at the midplane of the sample (Fig. 1) to facilitate the introduction of a flat crack normal to the axis of the cylinder. This is for the purpose of investigating the influence of normal stresses on the permeability of cracks in Indiana Limestone.



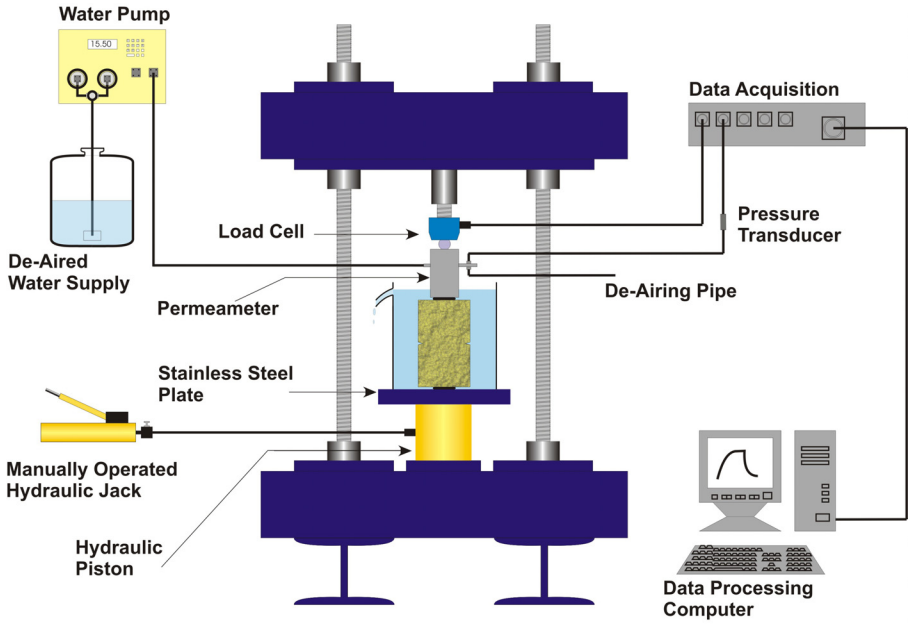
(a) **(b)**

Figure 1. The prepared sample: (a) shows the complete sample; (b) detail showing the epoxy coating around the drilled cavity.

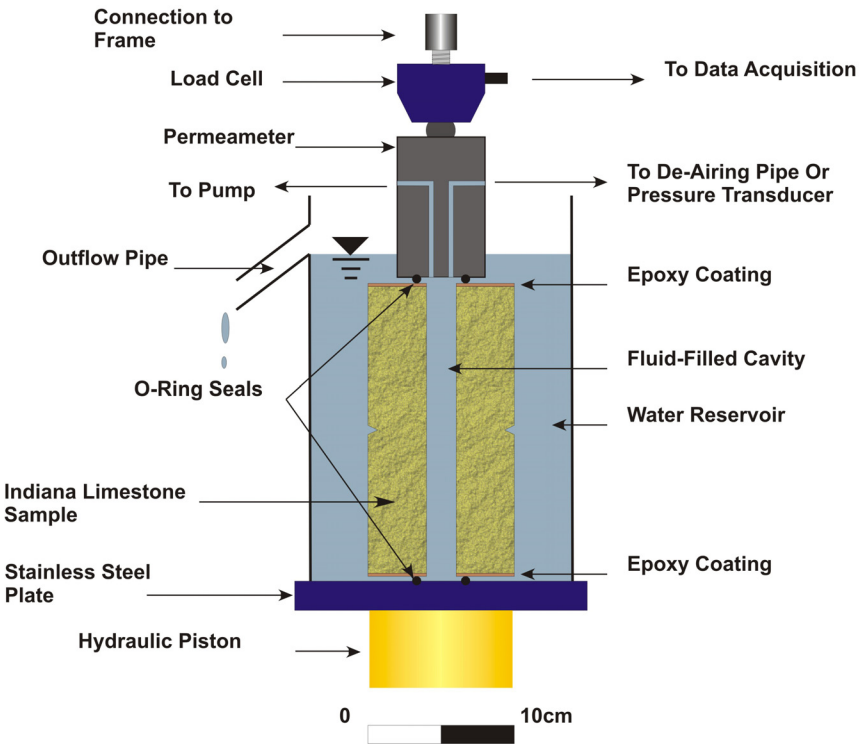
2.2 *Experimental setup*

In this research, constant flow steady state permeability testing was used, which involves the application of a constant flow rate to the internal sealed cavity of the sample. The sealing of the central cavity is achieved through the use of O-ring seals located at the base and the upper epoxied surfaces of the sample. The O-ring seal at the base of the sample is located directly in a groove located at the base plate of a water reservoir (Figure 2). The upper O-ring seal is located at the base of a stainless steel coupling that accommodates the following: (i) the water supply from a Shimadzu LC-8A medical pump that can accurately supply the flow rate, (ii) a connection to a pressure transducer that measures the cavity pressure, (iii) an outlet valve that allows drainage and can also be used to de-air the internal, fluid-filled cavity and (iv) a spherical seating that allows contact with a load cell that measures either loads required to seal the system or to apply a prescribed normal stress to a fracture aligned approximately normal to the axis of the limestone cylinder. The limestone sample is kept in a water reservoir made of Plexiglas and an outlet is provided to maintain a constant hydraulic potential on the outer cylindrical surface of the boundary. No special preparations are needed for the outer surface of the limestone cylinder since the flow is directed outwards from this surface. The reservoir containing the limestone sample is placed on the active surface of a hydraulic jack which allows movement of the experimental set-up so that the central cavity can be sealed for subsequent pressurization. The load cell connected to the stainless steel coupling can also be used to measure the normal stress acting on a fractured cylindrical specimen. The sealing capabilities of the O-rings were tested by pressurizing a metal cylinder containing a central cavity. It was found that a load of approximately 4 kN was sufficient to seal the central cavity and to apply a central cavity pressure of 150 kN/m^2. Maintaining constant cavity pressures over a 4 hour period was considered to be sufficient to develop an adequate seal. The experiments were performed in the Environmental Geomechanics Laboratory at McGill University and the temperature in the lab was maintained at approximately 22 ^{0}C. The temperature of the water varied between 20 ^{0}C and 23 ^{0}C. The instrumentation that includes the central cavity pressure and the axial load applied to the sample were recorded using a TracerDAQ data acquisition system.

The experimental set-up is shown in Figure 2. The steady state radial flow through the Indiana Limestone sample is attained by prescribing a constant flow rate to the Shimadzu LC-8A medical pump. A typical test on a sample involves first applying a reverse flow through the sample using a vacuum pump; this further cleans the cavity surface from any remaining rock debris. Flow through the sample is then re-initiated using the Shimadzu pump for at least 24 hours to ensure that the limestone sample is tested in a saturated condition. Once saturated, a constant flow rate is applied, usually 5 mL/sec, and the water pressure at constant time intervals, typically every 5 seconds, is recorded using the data acquisition system. Once a steady state pressure has been reached, the results as well as the average water temperature throughout the duration of the test are recorded and this procedure is repeated, typically 6 to 16 times. The data obtained is used to estimate the permeability of the tested sample.



(a)



(b)

Figure 2. (a) The experimental configuration for testing a drilled cylindrical Indiana limestone sample; (b) a cross-section of the sample, the O-ring seals and the permeameter.

3 RESULTS AND DISCUSSION

3.1 *Theoretical relationships*

The permeability of the intact drilled cylindrical limestone samples is determined using the steady state pressure obtained from the experiments in the following result (Selvadurai, 2000):

$$K = \frac{Q\mu \ln(b/a)}{2\pi H (p_i - p_e)} \tag{1}$$

where K = permeability (m^2); Q = flow rate (m^3/sec); μ = dynamic viscosity of water at the average temperature (kN.sec/m^2); b = external radius of the sample (m); a = radius of the cavity (m); H = height of the sample (m); p_i=cavity pressure at steady state (kN/m^2); p_e= pressure on the cylindrical exterior surface at steady state (kN/m^2).

3.2 *Experimental results*

Altogether six samples were tested in the radial flow configuration to determine the intact permeability. As expected, there were variations in the results both within the sample group and within the separate samples, with a slightly more noticeable variation between results on the separate samples. Table 1 shows the resulting average permeability value of each sample. Flow rates of 2, 3 and 5 mL/min were used during different experiments as an additional confirmation of repeatability. Figures 3 and 4 show the steady state pressures obtained in two typical experiments. As noticed in Figure 4, some cavity pressure readings of the experiments performed showed the occurrence of one or more pressure changes in the form of spikes. These irregularities were considered as noise caused by external voltaic influences on the data acquisition system. They were disregarded in the calculation of the steady state pressure since the steady state values were uninfluenced by these extremely short duration changes.

Table 1. Average permeability results of each sample tested.

Sample	Number of experiments	Average permeability × 10^{-15} (m^2)	Standard Deviation × 10^{-15}
1	15	0.984	0.0953
2	12	1.869	0.0952
3	11	1.277	0.173
4	10	1.417	0.0836
5	08	1.531	0.168
6	06	1.469	0.048

CONCLUSIONS

The results of the study performed on Indiana Limestone samples, extracted from the same Indiana Limestone block, show variations in permeability with only the slightest change in location. This emphasizes the importance of defining an acceptable range when assigning a value for the permeability of naturally occurring geological materials.

The radial flow permeability test is not a straightforward test for determining the permeability of geologic materials since the experimental configurations should assure that the seals that enable the application of the constant radial flow are effective and do not allow leakage that would give erroneous estimations of the permeability. In these tests, the experience gained with previous research investigations is put to good advantage to precisely define the test procedure.

The results of the experiments indicate permeability for the intact Indiana Limestone was in the range $0.984\times10^{-15}\,\mathrm{m}^2$ to $1.869\times10^{-15}\,\mathrm{m}^2$. The experimental data obtained in recent investigations involving *axial flow* in cylindrical samples indicate a permeability of $16\times10^{-15}\,\mathrm{m}^2$ at a $5\,\mathrm{MPa}$ confining pressure

(Selvadurai and Głowacki, 2008). A cuboidal sample of the same material is also being investigated using the surface permeability technique (Selvadurai and Selvadurai., 2009) which gives permeabilities ranging from $7\times10^{-15}\,\mathrm{m}^2$ to $97\times10^{-15}\,\mathrm{m}^2$.

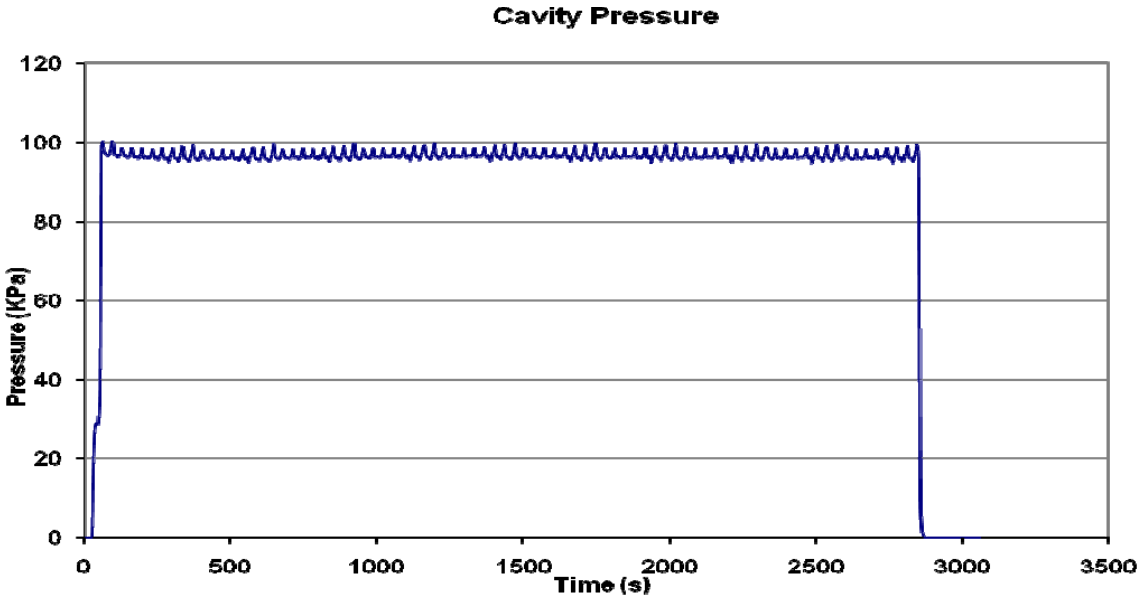


Figure 3. Time-dependent evolution of cavity pressure for the 12th experiment on sample 1 subjected to a 5mL/min flow rate.

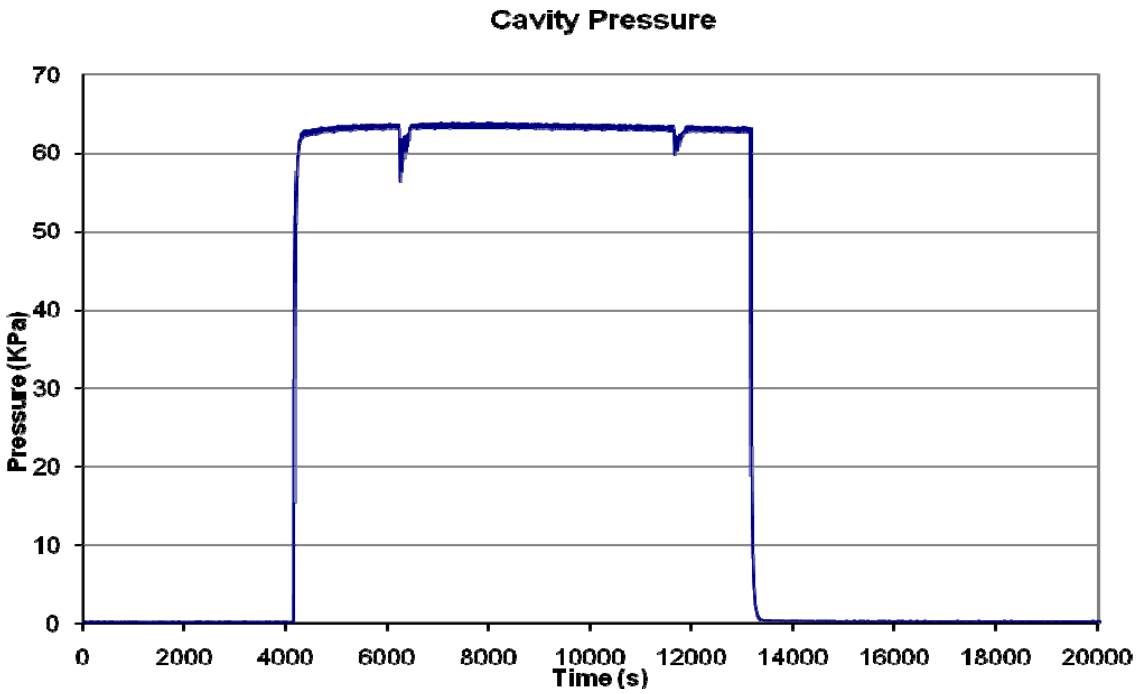


Figure 4. Time-dependent evolution of cavity pressure for the 6th experiment on sample 4 subjected to a 5mL/min flow rate.

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