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AN EXPERIMENTAL TECHNIQUE FOR DETERMINING THE PERMEABILITY OF ROCK, CONCRETE AND CEMENT GROUT

by

Paul Carnaffan

B.Eng. (Civil Engineering)

A thesis submitted
to the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
MASTER OF ENGINEERING*

Carleton University

Ottawa, Canada

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submitted by
Paul Carnaffan

in partial fulfilment of the requirements for the degree of
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Thesis Supervisor

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Abstract

There is an increasing interest in the application of engineering materials and natural geological materials as components of barrier systems. The permeability of these materials has a direct impact on the efficiency of the barrier systems to prevent the mass transfer of fluids.

The long term efficiency of many barrier systems is often evaluated using theoretical models since leakage through a barrier may be a process which takes months or even years to occur. These models invariably require a thorough knowledge of the properties of the materials being modelled. A review of the pertinent literature indicates a lack of a standardized test procedure for determining the coefficient of permeability of very low permeability materials such as concrete, cementitious grouts, and dense rock.

The objective of this research was to develop a laboratory test procedure for determining the permeability characteristics of rock, concrete, and cement grout within a reasonable time period and without the need for elaborate laboratory equipment.

The proposed test procedure used a right-cylindrical test specimen with a central cavity cored through it. The central cavity was pressurized and a transient analysis was used to evaluate the pressure decay response. An important aspect of the test development was the design of effective seals for such a pressure sensitive application.

The results of a test program carried out on cement grout test specimens suggest that the results are consistent and that the test can be performed quickly and accurately.

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List of Symbols

Symbol	Definition
a	radius of the central cavity (m)
A	cross-sectional area through which flow takes place (m^2)
b	an experimentally derived calibration factor
C	fluid compressibility (m^2/kN)
C_{eff}	effective compressibility of the test specimen as measured for a jacketed sample (m^2/kN)
C_s	compressibility of the minerals in the test specimen (m^2/kN)
C_w	compressibility of water (m^2/kN)
e	void ratio (non-dimensional)
E	Young's modulus (kN/m^2)
h	piezometric head (m)
h_u	hydraulic head in the upstream reservoir at time t (m)
H	hydraulic head in the upstream reservoir at time $t=0$ (m)
Δh	piezometric head difference between the sections at A and B (m)
i	hydraulic gradient (non-dimensional)
j	a variable defined in (2.11) (s^{-1})
k	coefficient of hydraulic conductivity (m/s)
K	coefficient of permeability (absolute permeability) (m/s)
K_e	effective permeability (m^2)
K_g	coefficient of permeability based on a gas permeability test (m^2)
K_L	coefficient of permeability based on a liquid permeability test (m^2)
K_p	modified permeability coefficient (m^2)
K_r	relative permeability (non-dimensional)

l	thickness (or length) of a test specimen (m)
l_a	thickness of an aquifer (m)
ΔL	distance between the sections A and B (m)
m	summation index
n	porosity (non-dimensional)
p	pore pressure within the test specimen (kN/m ²)
p_m	mean pressure at which gas is flowing during a gas permeability test measured in atm.
P_a	atmospheric pressure (kN/m ²)
P_D	pressure in the downstream reservoir (kN/m ²)
P_f	equilibrium pressure between the upstream and downstream reservoirs (kN/m ²)
P_o	pressure in the central cavity at time $t=0$ (kN/m ²)
P_r	reservoir supply pressure (kPa)
P_t	upstream fluid pressure at time t (kN/m ²)
$P(t)$	pressure in the central cavity at time t (kN/m ²)
P_U	pressure in the upstream reservoir (kN/m ²)
P_l	pressure at the end of the test specimen where the flowrate is measured (kN/m ²)
P_2	pressure at the opposite end of the test specimen from where the flowrate is measured (kN/m ²)
P_x	confining pressure (kN/m ²)
ΔP	pressure increase in the upstream reservoir (kN/m ²)
q	a variable which characterizes the permeability of a material (non-dimensional)
Q	flowrate through a cross-sectional area of porous material (m ³ /s)
r	radial extent (m); measured from the middle of the central cavity

s	slope of the linear portion of the semilogarithmic pressure decline curve (s^{-1})
S	storage coefficient (non-dimensional); defined in (4.3)
S_d	compressive storage of the downstream reservoir (m^2)
S_s	specific storage of the test specimen (m^{-1})
S_u	compressive storage of the upstream reservoir (m^2); it is defined as the change in volume of fluid in the upstream reservoir per unit change in hydraulic head in the upstream reservoir
t	time from the start of the test (s)
t_d	time from start of test to observed current drop (s)
T_r	transmissivity (m^2/s)
t_0	time at the start of the test (s)
v	discharge velocity (m/s); the quantity of water flowing in unit time through a unit gross cross-sectional area of soil normal to the direction of flow
V_D	volume of the downstream reservoir (m^3)
V_i	initial volume of fluid in the "thermal pump" (m^3)
V_U	volume of the upstream reservoir (m^3)
V_w	volume of water in the central cavity including volume in the load head and central cavity side of any valves (m^3)
x	distance along the length of the test specimen (m); measured from the upstream reservoir end of the test specimen)
γ_w	unit weight of water (kN/m^3)
μ	absolute viscosity ($kN\ s/m^2$)
ζ	a variable defined in (2.9) (s^{-1})
ψ	ratio of the compressive storage within the test specimen to the compressive storage of the upstream reservoir (non-dimensional)

ξ	ratio of the compressive storage of the downstream reservoir to the compressive storage of the upstream reservoir (non-dimensional)
φ	dimensionless time variable (non-dimensional)
α	non-dimensional variable defined in (4.11)
β	non-dimensional variable defined in (4.11)
ν	Poisson's ratio (non-dimensional)

1. INTRODUCTION

1.1 GENERAL

Permeability is generally recognized as the material property which governs the rate at which a fluid moves through the material. The permeability of soils is often measured using one of several standardized laboratory or field testing procedures. The permeability of materials such as cement grout, concrete, and dense rock is much smaller than that for most fine grained soils, with the result that for all practical purposes these materials are often considered to be impermeable.

Petroleum engineers have focussed on the determination of the permeability of dense rock formations for the past six decades, using a wide range of in-situ and laboratory test procedures. They utilize the permeability measurements to estimate yield rates from oil and gas-bearing formations and to optimize the design of injection and production wells. In recent years, there has been a renewed interest in the measurement of permeability of materials (notably concrete) by engineers involved in infrastructure rehabilitation, and geo-environmental engineers. In the context of infrastructure rehabilitation and preservation, engineers have identified permeability as a key property which will influence the durability of concrete, which in turn protects reinforcing steel from the detrimental effects of corrosion. In the area of concrete technology, engineers have suggested that in the specifications for concrete durability, the governing criteria should be based on considerations of permeability and diffusion of chemical species through concrete rather than on the traditional criteria which are solely based on strength

(Dhir and Byars, 1993). In the context of geo-environmental engineering, the assessment of permeability characteristics of natural rock is important to the determination of effectiveness of environmental remediation techniques involving the removal of hazardous and toxic materials and the provision of barriers consisting of cementitious materials such as grouts.

1.2 DEFINITIONS AND UNITS

Due to the diversity of applications involving the concept of permeability, there are a number of measures which describe the material parameters governing the flow of a fluid through a porous medium. This section will focus on a presentation of the various descriptions.

The terms *Absolute permeability (K)* and *intrinsic permeability (K)* are synonymous and they describe the permeability of a porous medium irrespective of the properties of the fluid migrating through the pore structure. The absolute permeability has units of length squared; the petroleum industry, however, uses the *darcy* or the *millidarcy* as the standard unit. A porous non-deforming material is said to have a permeability equal to 1 darcy if a pressure difference of 1 atmosphere will produce a flow rate of 1 cm³/s of a fluid with 1 centipoise viscosity through a cube having a side dimension of 1 cm. Hence

$$\begin{aligned} 1 \text{ darcy} &= \frac{1 \text{ (cm}^3\text{/s)} \quad 1 \text{ (centipoise)}}{1 \text{ (cm}^2) \quad 1 \text{ (atmosphere/cm)}} \\ &= 0.987 \mu\text{m}^2 \end{aligned}$$

For porous media with very low intrinsic permeability the unit millidarcy is used (1 millidarcy = 0.001 darcy).

The *hydraulic conductivity* (k) is a parameter which describes how easily a specific fluid passes through a porous medium. The hydraulic conductivity takes into account the properties of both the fluid and the porous medium (Haimson and Doe, 1983), and has the same units as velocity (usually m/s).

The hydraulic conductivity is related to the absolute permeability by the equation:

$$k = \frac{\gamma_w K}{\mu} \quad (1.1)$$

where	k	=	coefficient of hydraulic conductivity (m/s)
	K	=	coefficient of absolute permeability (m ²)
	γ_w	=	unit weight of water (kN/m ³)
	μ	=	absolute viscosity of water (kN s/m ²)

The recurring confusion surrounding the terminology associated with permeability testing is due to the fact that Darcy's law relating the velocity of fluid flow through a porous material to the hydraulic gradient across the material is expressed using the coefficient of hydraulic conductivity, rather than the coefficient of intrinsic permeability. The basis for many experimental procedures and their associated analysis techniques is largely developed with the assumption concerning the validity of Darcy's law. The definition of Darcy's law is given by equation (1.2). Figure 1.1 shows the physical model used in the development of Darcy's law.

$$v = k i \quad (1.2)$$

where v = discharge velocity (m/s); the quantity of water flowing in unit time through a unit gross cross-sectional area of soil normal to the direction of flow

i = hydraulic gradient (non-dim.)

The hydraulic gradient is defined as:

$$i = \frac{\Delta h}{\Delta L} \quad (1.3)$$

where Δh = hydraulic potential difference between the sections at A and B (m)

ΔL = distance between the sections A and B (m)

Many researchers express test results in a form corresponding to hydraulic conductivity and do not use the relationship given by (1.1) to account for the influence of the properties of the fluid.

The absolute permeability can only be determined experimentally when the porous structure of the material is completely saturated with a single fluid phase. The term **effective permeability** (K_e) is used to describe the apparent permeability of a material to a particular fluid while the material is saturated with a multiple-fluid phase (e.g. water flowing through an unsaturated porous medium or a medium saturated partly with water and partly with oil or any other viscous fluid).

Figure 1.1 Physical model used in the definition of Darcy's law.

Relative permeability (K_r) is defined as the ratio of the effective permeability to the absolute permeability (see equation 1.4).

$$K_r = \frac{K_e}{K} \quad (1.4)$$

where K_r = relative permeability (non-dim.)
 K_e = effective permeability (m^2)
 K = absolute permeability (m^2)

Transmissivity (T_r) is a property of an aquifer and is a measure of its ability to transmit water. It is defined as the product of the hydraulic conductivity and the thickness of the aquifer (see Figure 1.2 and equation (1.5)). The units associated with transmissivity are therefore length squared per unit of time.

$$T_r = k l_a \quad (1.5)$$

The term **permeability** will be used throughout the remainder of this thesis in its true sense, that is, to mean absolute permeability, K with units of m^2 .

$$T_r = kl_a$$

Figure 1.2 Definition of transmissivity.

1.3 RATIONALE FOR MEASURING PERMEABILITY

1.3.1 APPLICATIONS TO EVALUATION OF INFRASTRUCTURE DURABILITY

Much of the existing infrastructure in North America is made of reinforced concrete. Applications of concrete in civil engineering structures have a strong historical precedent and include such structures as buildings, bridges, roadways, dams, pipes, earth-retaining structures and water-retaining structures. In most of these examples, the concrete provides much of the structural integrity required to withstand the loading conditions which will be imposed on the structure throughout its design life. In some cases, however, the concrete is expected to fulfil other functional criteria and most notably act as a barrier to the migration of water.

The importance of the permeability characteristics of concrete is quite evident in applications such as underground pipes and water-retaining structures where the permeability must be sufficiently low to prevent visually-detectable leakage out of pressurized water-retaining structures or groundwater migration into non-pressurized pipes (e.g. see Figure 1.3). In purely "structural" applications, the most important function of the concrete is to act as a medium which integrates the reinforcing action of steel. The secondary function is to protect the steel from detrimental actions of corrosion and exposure to the atmosphere (see Figure 1.4). Hearn and Mills (1991) state that the concrete cover serves to prevent diffusive mass transfer of water, water vapour, gas and ions into the body of the concrete where reinforcing steel and certain types of aggregates may be susceptible to attack (e.g. alkali-aggregate reactions which deteriorate the concrete). The adequacy with which the concrete cover fulfils this function has a considerable

Figure 1.3 Examples of concrete infrastructure where the concrete serves as a barrier to fluid penetration.

Intact concrete protecting the reinforcing steel from the environment

Cracked concrete allowing environmental agents to attack and corrode the reinforcing steel

Figure 1.4 Concrete serving as protection for reinforcing steel from corrosion and exposure to the atmosphere.

impact on the longevity of the structure and its structural integrity. The permeability of concrete is therefore a key property which can influence issues related to durability of structural materials.

The resistance of concrete to damage from freezing and thawing can be dependent on the permeability of the cement paste. The deterioration is due to hydraulic pressures generated within the cement paste and/or aggregate as unfrozen water is displaced during the expansion of water during ice crystal formation (there is a 9% increase in volume of water during freezing) (Kosmatka et. al., 1991). It is therefore important for the outer surface of the concrete to sufficiently inhibit saturation of the pores so that expansion-induced displacement of water does not create adverse stresses in the microstructure of the concrete.

Currently, there are no CSA or ASTM standardized tests for measuring the permeability of concrete. Consequently, scientists and engineers have developed a variety of techniques for the measurement of properties related to permeability: these include water absorption tests (see e.g. Kay, 1992), gas permeability tests and water permeability tests. Some of the tests currently in use do not actually directly measure the permeability of the concrete; they only give relative estimates for the permeability or an index number providing a qualitative assessment between different mix designs (e.g. concrete mix A is less permeable than concrete mix B). It would seem clear that a standard test is required in order that useful comparisons can be made between results for the purpose of evaluating the durability of the concrete from permeability measurements.

1.3.2 APPLICATIONS TO WASTE CONTAINMENT

The geological disposal concepts for hazardous wastes often require the assessment of permeability characteristics of concretes and natural geological materials such as rocks. An example of this relates to the disposal of highly-radioactive wastes which result from the energy production by nuclear reactors. For example, the irradiated heat-emitting spent fuel resulting from CANDU reactors is currently stored in water pools in concrete bays (see Figure 1.5). Even at this stage, the permeability characteristics of the concrete are important to the safety of the temporary storage (Dixon and Rosinger, 1984, Wright, 1991). In the Canadian context, the long-term disposal of such waste calls for the construction of deep vaults in granitic rock formations in the Canadian Shield (Lyon, 1980) (see Figure 1.6). Although a series of multiple engineered barriers are used in such a repository (e.g. waste containers, engineered clay buffers, backfill, etc.) the natural geological medium plays an important role in attenuating any long term effects of radionuclide migration. In this context, the permeability characteristics of the natural geological material are important to the accurate evaluation of the radionuclide release rates. In such deep disposal concepts, cement grouts have been proposed as techniques for sealing fractures in the vicinity of a repository and the galleries and shafts which will be constructed for access. The permeability characteristics of the cement grout and the permeability of the interface between the grout and the concrete are therefore of critical importance to the waste management effort. In other applications, it is proposed that the containers which house low-level radioactive wastes could be encapsulated in concrete. The efficiency of this dry storage scheme will be influenced by the permeability

Figure 1.5 Schematic view of water-filled concrete storage bay for short term disposal of irradiated spent fuel.

Figure 1.6 Borehole emplacement scheme for long term disposal of irradiated spent fuel in deep vaults in granitic rock formations in the Canadian Shield.

characteristics of the concrete.

In all of the waste containment applications described here, the objective is to isolate the hazardous materials from the geosphere and the biosphere. It is therefore of considerable importance to prevent (or at the least, severely inhibit) the movement of fluids both into and out through the containment boundaries. Due to the potentially serious environmental impact of even a small leak over a period of many years, the permeability of the rock or concrete is a very important property in determining the effectiveness of the barrier material.

In recent years, there has also been a growing interest in the use of concrete for stabilization and solidification of toxic waste (see e.g. Poon et al., 1986). This investigation identified permeability as an important property governing the durability and leachability of solidified waste materials.

1.4 OBJECTIVES AND SCOPE OF THE THESIS

The objective of this thesis was to develop a method for the accurate determination of the permeability of cementitious materials and dense rocks. The new technique should offer advantages over the test procedures which are currently available. Ideally, any new test should be (1) easy to perform, (2) give consistent results and (3) require comparatively-less-complicated equipment than those currently used.

The scope of the thesis primarily focussed on the development of the test equipment and test procedure. The test data were amenable to analysis via solutions available in the literature. Since the scope was limited to the design of the experimental

technique, the testing program was developed as a technique to modify and refine the test procedure and equipment. Once the test development was completed, a series of tests were performed to assess the consistency of the test results.

2. LITERATURE REVIEW

2.1 FACTORS AFFECTING PERMEABILITY MEASUREMENT

Although permeability is considered to be a material property, there are several factors other than the test sample which can influence the apparent test results. These include the stress state in the sample, chemical effects, the degree of saturation and the characteristics of the permeating fluid. These factors can change the "measured" permeability of a sample by as much as several orders of magnitude.

2.1.1 STRESS CONDITIONS

The state of stress within the sample can have a considerable influence on the permeability of a material. Large stresses (i.e. stresses such as those found deep in the earth) can cause deformation of the pore skeleton, possibly closing small cracks and shrinking the pores. Brace et al. (1968) conducted tests on Westerly granite samples which were subjected to confining pressures as high as 400 MPa and found that permeabilities reduced from $350\text{E-}19 \text{ m}^2$ at 5 MPa pressure to $4\text{E-}21 \text{ m}^2$ at 400 MPa pressure. Knutson and Bohor (1963), Bernaix (1966), Kranz et al. (1979) and Heystee and Roegiers (1981) have also found reductions in the permeability due to large confining pressures. The results of these investigations indicate that an increase in the state of stress generally results in a reduction in the permeability of the porous medium. The test procedures used by many of these researchers will be discussed in section 2.2. Heystee and Roegiers (1981) also reported on increases in permeability in rock masses under tensile stresses.

The results of these investigations suggest that the state of stress in the sample should be taken into account when either selecting or designing a permeability test, or when interpreting test results. It is usually desirable to test the sample in a state of stress which duplicates, as closely as possible, the state of stress under field conditions.

2.1.2 CHEMICAL EFFECTS

Geochemical reactions can occur between the permeating fluid and the test sample. In a test environment, this can usually be avoided by selecting a fluid which is chemically-inert with respect to the porous material. Examples of such inert fluids include demineralized water (Freeman and Bush, 1983), kerosene (Kranz et al, 1979) and mineral oil (Heystee and Roegiers, 1981). In some instances, the permeating fluid can dissolve and flush out minerals, and in other instances, the permeant may leave mineral deposits on the pore skeleton. Sample preparation techniques have also been used to minimize chemical effects. In testing sandstone samples, Freeman and Bush (1983) subjected the cores to heating at 427 °C for 6 hours in order to break down some of the clay minerals present in the rock, thereby minimizing the sensitivity to fresh water.

Chemical effects are particularly difficult to control when testing samples made of cement paste. This can be largely attributed to the hydration process in a cement paste. The water migrating through the concrete during the test reacts with the unhydrated regions of cement particles to form hardened cement paste. This hydration process can result in a reduction in the pore volume and consequently the permeability.

Since steady-state tests usually require long durations to reach equilibrium, significant changes in the permeability of the concrete can occur throughout the duration of a test. Banthia and Mindess (1989) developed a sample conditioning technique which attempts to achieve steady-state conditions within one day. This procedure presupposes that the effects of continued hydration of cement particles will not have a significant influence on the test results. The conditioning technique involves periodic reversal of the flow (or flushing), under high hydraulic gradients, in order to saturate the sample. They used this procedure to investigate the effect of curing time on the permeability of hardened cement pastes. Even with this procedure there is no assurance that the effect of the hydration process can be totally eliminated during the test.

2.1.3 DEGREE OF SATURATION

In order to measure the permeability of a material, its pore space must be fully saturated with the fluid phase. In practice, it implies that for a water-based permeability test, all air within the communicating pores must be removed and replaced with water. The complete saturation process can be difficult and time-consuming to achieve, particularly for large samples. For gas-based permeability tests, any moisture within the sample must be removed (ie., the sample must have a 0.0% moisture content). Such a dry condition would be difficult to achieve without drying the test specimen in an oven. Such a procedure could result in shrinkage cracking (Cabrera and Lynsdale, 1988). Incomplete drying will leave a residue of water in the smaller pores, and this water can, by virtue of surface tension effects, impede the movement of gas, thereby reducing the

effective flow rate through the sample (Cabrera and Lynsdale, 1988). Reductions in gas permeability by 75 times has been reported between oven-dried samples and saturated samples (Bamforth, 1987). Hearn and Mills (1991) found that it was necessary to normalize gas flow data at a standard moisture content. This will give a standard reference but not the true permeability coefficient of the porous material.

Techniques for saturating samples with liquid vary from allowing it to stay submerged in liquid (Dewaele et al., 1991) to vacuum saturation (Hearn and Mills, 1991) to simply forcing the liquid through (Banthia and Mindess, 1989). In instances where liquid is forced through the sample it is necessary to establish that such a procedure will not result in micro-cracking of the porous medium which can alter the permeability of the material.

2.1.4 PERMEATING FLUID

The viscosity of the permeating fluid is accounted for in the calculations which determine the coefficient of permeability of a material. The compressibility of the fluid can also be accounted for in the analysis. Therefore, in principle, it should not make a significant difference whether the permeating fluid is water, air or kerosene (for example). Studies have, however, shown that permeabilities determined using a gas as the permeating fluid (as opposed to a liquid) are almost always higher (Bamforth, 1987, Ahmed et al., 1991). Gas permeabilities as much as 78.5 times that of the water permeabilities have been reported by Bamforth (1987). The discrepancy between liquid and gas permeability measurements becomes larger as the permeability decreases. The

discrepancy has been attributed to a phenomenon called gas slippage, also known as the *Klinkenberg effect* (Ahmed et al., 1991). Gas slippage is the term used to describe the observation that a gas has a higher velocity near a grain surface than does a liquid. As a result, the quantity of gas flowing through a capillary is larger than that predicted by Poiseuille's equation (Bamforth, 1987).

Klinkenberg (1941) and Bamforth (1987) have proposed corrections to gas permeability results to account for the Klinkenberg effect. Klinkenberg (1941) proposed an empirical relationship to convert permeability coefficients from gas tests to the equivalent liquid-based permeability coefficient (Bamforth, 1987). The relationship was based on the results of experimental tests on a limited number of oil sands and core samples and can be expressed as follows:

$$K_L = \frac{K_g}{\left(1 + \frac{b}{p_m}\right)} \quad (2.1)$$

where b is an experimentally-derived calibration factor defined by

$$b = 0.777 K_L^{-0.35} \quad (2.2)$$

and where K_L = coefficient of permeability based on
a liquid permeability test (m^2)

K_g = coefficient of permeability based on
a gas permeability test (m^2)

p_m = the mean pressure at which gas is
flowing (atm.)

Bamforth (1987) later modified Klinkenberg's expression by developing a more general form for the constant b ; this was based on test results from four different concrete mixes as well as from the data given in Klinkenberg's tests.

Due to the absence of a satisfactory analytical relationship, it is preferable to use liquid-based permeability tests if the intrinsic permeability of a very low permeability material is sought.

2.2 METHODS OF DETERMINING PERMEABILITY

The need for accurate determination of the coefficient of permeability of low permeability materials such as concrete and crystalline rocks was discussed in Chapter 1. Many different tests are currently being used to determine the coefficient of permeability of such materials, however, none of these tests have been adopted as a standard by agencies such as ASTM or CSA.

The remainder of this chapter is devoted to a literature review of the types of permeability tests currently in use and a critical evaluation of the advantages and disadvantages associated with these techniques.

Figure 2.1 shows a general scheme of the major categories of permeability tests available. In general, all permeability tests can be classified as either laboratory testing techniques or as in-situ testing techniques. In-situ permeability testing generally gives a value for permeability which is representative of the overall permeability of a test region (such as a length of borehole) including the effects of fractures, fissures, anisotropy and non-homogeneity within that region. Laboratory test techniques are carried out on small

test specimens (e.g. 150 mm in diameter by 300 mm in length or smaller). The relatively small size of the test specimen usually ensures that the test material is in an intact state and that the chemical and pore structures of the material are not expected to vary significantly throughout the test specimen.

The testing procedures which are of direct importance to the work presented in this thesis are the laboratory test techniques. The permeability values obtained from such tests are applicable to the applications discussed in Chapter 1 for the ensuing reasons:

- (1) Most concrete structures are designed to remain relatively intact and homogeneous on a large scale (i.e. although concrete is non-homogeneous by nature, its properties and composition will be reasonably uniform along the length of a structural element such as, for example, a beam).
- (2) Intact rock formations with relatively uniform and homogeneous properties are usually sought as sites for waste disposal facilities. Variations in permeability over a site can be accounted for by testing many samples (at various locations and at various depths) and keeping a record of their locations.
- (3) The permeability of intact rock can be used in conjunction with theories of flow through fractures to model natural rock formations.

The in-situ permeability testing techniques will be briefly discussed since these techniques have a bearing on some of the laboratory techniques.

Figure 2.1 General scheme of the basic categories of permeability testing.

2.2.1 IN-SITU PERMEABILITY TEST TECHNIQUES

The *packer test* is the most common method for measuring the permeability of rock formations. In this method, a test section of an exploratory drillhole is isolated by internally sealing the hole with an inflatable "packer". A single-packer system uses a single inflatable section and seals between the base of the drillhole and the inflatable "packer". A double-packer system seals a length of drillhole between two inflatable "packers". Schematic views of both the single and double-packer systems are shown in Figure 2.2. A known flowrate is injected into the isolated section of the drillhole and the total head in the test section and in an observation well a distance R from the test hole are recorded once a steady-state condition has been reached. The hydraulic conductivity is calculated using the following relation:

$$k = \frac{Q}{2\pi l(H_1 - H_2)} \ln \left(\frac{2R}{D} \right) \quad (2.3)$$

where	k	=	hydraulic conductivity (m/s)
	Q	=	injection rate (m ³ /s)
	l	=	length of test section (m)
	R	=	distance from the test hole to the observation well (m)
	D	=	diameter of the drillhole (m)
	H_1	=	total head in the test section (m)
	H_2	=	total head in the observation well (m)

Figure 2.2 Packer permeability test methods. (a) Single-packer test.
 (b) Double-packer test.
 (after Franklin and Dusseault, 1989)

The most commonly performed packer tests do not use an observation well. These simplified packer tests use an empirically-derived coefficient which depends on the ratio of hydraulic conductivities parallel and perpendicular to the test hole along with the injection rate and the total head in the test section to evaluate the 'average' hydraulic conductivity of the rock formation in the test section. The empirical coefficient chosen is based on a visual evaluation of the isotropy of the rock formation (Franklin and Dusseault, 1989).

Packer tests can also be used to perform *pulse tests*. In this technique, the section of drillhole to be tested and the tubing to the packer are filled with water, then very rapidly pressurized to 300 kPa or 600 kPa and the pressure shut in. The pressure decay within the test section is recorded and the transmissivity of the test section determined by using a curve-matching technique developed by Bredehoeft and Papadopoulos (1980). An alternative method of analysis was developed for analyzing pulse test data from tests on sections of rock with single fractures of infinite and finite extent.

Borehole *recharge tests* or "slug tests", although not very accurate, can be used to provide an estimate of the permeability. The elevation of the water table is measured in the borehole and then the water level is lowered. The rise of water in the borehole over a period of time is recorded. This data can be used with an empirical relationship to estimate the average permeability of the material surrounding the borehole. Exact mathematical solutions can also be used to calculate the permeability.

2.2.2 LABORATORY PERMEABILITY DETERMINATION TECHNIQUES

2.2.2.1 STEADY-STATE PERMEABILITY TESTS

Steady-state determination of permeability involves either the application of a constant pressure gradient across a sample and the measurement of the corresponding steady-state flow rate, or the application of a constant flow rate through the sample and the measurement of the corresponding equilibrium pressure that develops. The constant pressure gradient test is by far the more common of the two techniques, but both techniques have advantages.

The advantage of steady-state tests is the simplicity in the analysis. In almost all cases, the analysis is simply an application of Darcy's law.

Since we measure the flowrate and the hydraulic gradient in most test procedures, it is more convenient to express Darcy's law as:

$$Q = Aki \quad (2.4)$$

where

Q	=	the flowrate through the sample (m^3/s)
A	=	the cross-sectional area of the sample (m^2)
i	=	the hydraulic gradient (non-dim.)

For tests using a gas as the permeating fluid, Darcy's law must be combined with the Poiseuille equation. The permeability obtained from a steady-state gas permeability test is therefore expressed as (Bamforth, 1987), (Poon et al., 1986):

$$K = \frac{2Ql\mu P_1}{(P_2^2 - P_1^2)A} \quad (2.5)$$

where	K	=	coefficient of permeability (m^2)
	l	=	thickness of specimen (m)
	Q	=	flowrate through the specimen (m^3/s)
	μ	=	absolute viscosity of the gas ($\text{kN s}/\text{m}^2$)
	A	=	cross-sectional area of specimen (m^2)
	P_1	=	pressure at the end of the specimen where the flowrate is measured (kN/m^2)
	P_2	=	pressure at the opposite end of the specimen from where the flowrate is measured (kN/m^2)

The primary disadvantage of the steady-state technique is that for very low permeability materials, such as rock or concrete, investigations have shown that long periods of time are required to fully saturate a sample and to reach a steady-state flow condition (Poon et al., 1986; Banthia and Mindess, 1989; Ahmed et al., 1991). Tests conducted by Powers et al. (1954) on approximately 25 mm diameter by 12 mm thick tapered cylindrical samples of cement pastes and rocks required durations as long as 4 weeks to reach steady-state conditions.

The second disadvantage with steady-state testing of low permeability materials is that the flow rates generated, even under extremely large pressure gradients, are extremely small (sometimes only fractions of a millilitre per hour). Accurate measurement of these low flow rates, either by flowmeters, by volume, or by mass can

be extremely difficult due to reading errors in the equipment used or due to evaporation of the permeant. The steady-state tests in which a constant flow rate is forced through the sample avoid the problem of measuring extremely low flow rates, but can result in extremely large or extremely low equilibrium pressures. This wide range for the equilibrium pressure implies that the person conducting the test needs to possess a reasonably good initial estimate of the permeability in order to set the flowrate at a level which will generate pressures within the capabilities of the test equipment.

The most common configuration for steady-state permeability tests is a cylindrical sample with laminar flow occurring along its length. Typically, a constant pressure gradient is applied over the length of the sample and the flowrate of the fluid through the sample is measured. The general constant head test just described is often used in testing coarse-grained soils with high permeabilities. When this test method is applied to rock or concrete core samples, the following problems can occur. First, for the very low permeabilities associated with rock and concrete (e.g. less than $1.0\text{E-}18 \text{ m}^2$), extremely large hydraulic gradients are required to produce an accurately measurable flowrate. Goto and Roy (1981) have documented permeability tests on hardened cement pastes where the samples have been subjected to hydraulic gradients as large as 35,000. Second, when testing core samples, there is a likelihood that secondary flow might take place between the sample and the sample holder. This leakage can be substantial and may even be as large as the flow through the sample. The interface conditions, pressures applied to the sample and the deformability characteristics of the sample can all influence the interface flow processes.

Some of the earliest versions of constant head permeability tests for rock cores were those performed in triaxial cells. Daw (1971) discussed a permeameter made by modifying a commercially available Hoek-Franklin triaxial cell. This permeameter is shown in Figure 2.3, and is suitable for performing tests using either a gas or a liquid as the permeating fluid. The test specimen, which had dimensions of 25 mm in diameter by 25 mm in length, was sealed around the circumferential face by high pressure applied to the outer side of a rubber sealing sleeve. Tests on a metal blank, in place of the rock specimen, showed that the confining pressure must be 1.2 times the applied fluid pressure (i.e., the pressure forcing flow through the sample) for smooth walled cores and 2.0 times the applied pressure for rough walled cores. The brass seat and plunger each contains a 5 mm diameter flow channel and a slightly recessed area on the face which is in contact with the sample. The recessed area ensures equal flow over the cross section of the sample. The cell has been used to measure hydraulic conductivities in the range of 10^{-5} m/s to 10^{-12} m/s.

A modified triaxial cell was also used by Banthia and Mindess (1989) for investigations into the effects of curing time on the permeability of hardened cement pastes. Banthia and Mindess (1989) tested 50 mm diameter by 6 mm thick specimens at hydraulic gradients of 2,380. Banthia and Mindess (1989) developed a sample-conditioning technique for use with this type of permeability cell. The conditioning technique was found to decrease the period of time required to reach steady-state flow conditions and involved subjecting the test specimens to repeated cycles of flow reversal at hydraulic gradients greater than those used during the test itself.

Figure 2.3

A modified Hoek-Franklin triaxial cell. The modifications allow the cell to be used for permeability testing of rock. (after Daw, 1971)

Another version of the steady-state constant hydraulic gradient test is that reported by van der Muelen and van Dijk (1969) and also by Bamforth (1987), in which the core has an epoxy ring cast around it. Figure 2.4 shows a schematic view of the permeability cell used by van der Muelen and van Dijk (1969) and the Figure 2.5 shows the permeability cell used by Bamforth (1987). van der Muelen and van Dijk (1969) tested specimens of concrete which were 75 mm in diameter and 25 mm thick. Bamforth (1987) used concrete test specimens which were 100 mm in diameter by 50 mm thick. The smooth epoxy ring is sealed against the brass walls of the cell with an o-ring. The advantage of this set-up is that no confining pressures are applied to the test specimen. The primary disadvantage is that a considerable amount of specimen preparation is required before a test can be performed. Furthermore it is difficult to reuse the specimen for other types of tests and prohibitively-long periods of time are required to saturate the specimen and to reach steady-state conditions. Bamforth (1987) performed tests using water as the permeating fluid and using pressures of up to 1,000 kPa. The method of analysis is once again based on Darcy's law, however, Bamforth (1987) also presented an approximate method of analysis, based on the depth of penetration of the permeating fluid, which can be used to determine the permeability characteristics of very low permeability materials.

Hearn and Mills (1991) proposed a permeameter in which the test specimen was sealed within a Room Temperature Vulcanised (RTV) silicone rubber ring. The RTV rubber ring fitted snugly within an outer aluminum ring. The Figure 2.6 shows a schematic view of the cell and the overall test set-up used by Hearn and Mills (1991).

Figure 2.4

Permeability cell with sample sealed within epoxy casing.
(after van der Muelen and van Dijk, 1969)

Figure 2.5

Permeability cell with sample sealed in epoxy casing.
(after Bamforth, 1987)

Figure 2.6

Schematic view of the sealing mechanism and overall test set-up used by Hearn and Mills. (after Hearn and Mills, 1991)

The permeameter was designed for performing permeability tests on cement and concrete specimens in the form of discs 100 or 150 mm in diameter and 25 to 60 mm thick. When the top end plate is installed, it compresses the RTV ring axially, thereby causing it to expand radially and form a seal between the aluminum ring and the test specimen. Hearn and Mills (1991) chose to use this system because they found that the membrane in the modified Hoek-Franklin triaxial cell was difficult to install and needed frequent replacement. The RTV rubber ring provides a convenient and effective seal with minimal sample preparation and without the application of large loads on the sample.

In the experimental procedure proposed by Hearn and Mills (1991), a hanging weight was applied to a piston head in a pressure cylinder in order to provide a constant pressure supply of de-aired water for the tests. The flowrate is measured at the outflow end of the sample by collecting the water in a water-filled piston. The piston head prevents evaporation and rises as the water flows out of the sample and into the piston. The vertical displacement of the piston head is recorded using a Linear Variable Differential Transformer (LVDT), and then multiplied by the cross-sectional area of the piston to evaluate the flowrate.

The concept of using radial expansion of a rubber ring to seal the circumference of a test specimen had previously been used by Poon et al. (1986) and Cabrera and Lynsdale (1988). Poon et al. (1986) used an inflatable inner tube to produce the radial expansion and thereby forming a seal. Cabrera and Lynsdale (1988) applied an axial load to the top of a rubber ring in a manner similar to that described in the tests by Hearn and Mills (1991).

Goto and Roy (1981) presented results which were obtained by using a pressure chamber which housed both the test specimen and the pressurized water supply. The test specimens were hardened cement paste discs 25 mm in diameter by 10 mm thick. The de-ionized water was pressurized to 3,500 kPa by a floating piston head in the cylinder which was pushed by nitrogen gas from a nitrogen tank. This test set-up is shown in Figure 2.7.

A steady-state, constant-pressure-gradient permeability test with radial flow conditions was used by Heystee and Roegiers (1981). In this case, the analysis is still based on the validity of Darcy's law, but uses a radial flow geometry, much like the analysis of a pumping test carried out in a fully-penetrating well in a confined aquifer.

Heystee and Roegiers (1981) tested cores of Indiana limestone, granite and red sandstone which had dimensions of approximately 64 mm in diameter by 100 mm in length with a 6.4 mm diameter hole drilled along the central axis to within 13 mm of the base of the cylinders. The top and bottom surfaces of the cylinders were sealed with an epoxy resin. A tube fitting was epoxied into place at the top of the cylindrical cavity in the cylindrical specimen. The final configuration of the experimental facility, shown in Figure 2.8, was assumed to give approximately radial flow conditions. The core was housed within a high-pressure cell rated to a fluid pressure of 70 MPa. The cores were saturated with the permeating fluid, mineral oil in these tests, and then tested under convergent flow conditions. In the convergent flow tests, the fluid in the cell was pressurized and maintained at a constant level, until a constant flow out of the central

Figure 2.7

Floating piston type permeameter. (After Goto and Roy, 1981)

Figure 2.8

Radial flow permeameter. (After Heystee and Roegiers, 1981)

cavity was achieved. The convergent flow tests allow for the investigation of the effects of confining pressures (compressive) on the coefficient of permeability of porous media.

In the divergent flow tests, the fluid was forced into the central hole under a constant pressure, and the outflow from the pressure cell was measured. The divergent flow tests allow for the investigation of the effects of tensile stresses on the coefficient of permeability of porous material.

A different approach to the steady-state test is to force a constant flow rate through the test specimen and to measure the steady-state pressure that develops. The "flow-pump method" was introduced by Olsen (1966) and has been used by Olsen et al. (1985) for measuring the permeability of silty sand and silty clays. Although there is no evidence of the use of this technique for the measurement of the permeability of rock, it could be used to avoid the problem of measuring extremely small flowrates.

Many of the permeameters already described, for use in liquid permeability tests, (e.g., the permeameters developed by van der Muelen and van Dijk (1969), Daw (1971) and Hearn and Mills (1991)), can also be adapted for gas permeability tests simply by changing the pressure supply system and the equipment used for measuring the flow rate. The test cell, sealing method and method of analysis will generally remain the same.

Bamforth (1987) modified the sealing mechanism of his permeameter for use with gas (nitrogen gas is used as the permeating fluid). The cast epoxy ring is replaced by a brass collar with a sealing coat of epoxy resin on the circumferential face. Gaskets around the perimeter of the test specimen at both the top and the base of the sample sealed the specimen between the steel end plates. A schematic view of the modified

permeability cell is shown in Figure 2.9.

Bamforth (1987) used the liquid and gas cells to compare the influence of the permeating fluid on the results obtained from the two types of permeability tests. The differences in the permeability coefficients obtained were attributed to the gas slippage theory, and a correction was applied to the results obtained from the gas permeability tests to convert them to equivalent liquid permeability values.

Poon et.al. (1986) presented an oxygen permeability cell for measuring the permeability of concrete. The seal around the circumference of the specimen is achieved with a soft PVC (polyvinyl chloride) collar which is pressed against the specimen by an inflatable inner tube. This permeability cell is shown in Figure 2.10. The flow rate is measured using a rotameter.

Cabrera and Lynsdale (1988) used a gas permeability cell which had a silicone rubber, frustum shaped, hollow cylinder which contracted radially to seal against the test specimen. This contraction is achieved during the application of an axial load to the sealing plate. (This same general concept was used by Hearn and Mills (1991) in their experiments). The tests were performed at a pressure of 100 kPa and the flow rate was measured with a bubble flowmeter. The sealing technique is shown in Figure 2.11.

Figure 2.9

Gas permeability cell. Modification of permeameter shown in Figure 2.5 (after Bamforth, 1987)

Figure 2.10

Permeameter with an inflatable tube to provide the circumferential seal. (after Poon et al., 1986)

Figure 2.11

Permeability cell which seals the specimen by radial expansion of a hollow silicone rubber cylinder when axial load is applied to the rubber. (after Cabrera and Lynsdale, 1988)

2.2.2.2 PERMEABILITY DETERMINATION BY TRANSIENT METHODS

A transient flow method of determining permeability was introduced by Brace et al. (1968). The tests were performed on cores of Westerly granite which were 16.1 mm long and 25.2 mm in diameter. The ends of the specimens had been ground to ensure that they were right cylinders. The experimental facility consisted of a pressure supply, a pressure transducer, valves and a pressure cell. The confined specimen arrangement is shown in Figure 2.12 and consists of the test specimen, two 0.5 mm thick number 200 mesh screens, a hardened steel alloy plug which serves as the downstream reservoir and a hollow piston which connects to the pressure supply and transducer, and which also serves as the lid of the pressure cell and upstream reservoir. A 3 mm thick polyurethane rubber jacket surrounds the sample and is held in place by wire clamps.

The test procedure is quite straight forward. The upstream reservoir (denoted by subscript U) and the downstream reservoir (denoted by subscript D) are filled with water. The pressure cell is also filled with water, then pressurized to a constant confining pressure, P_{Σ} . The reservoirs are then pressurized to a constant pressure ($P_U = P_D = p$). At the start of the test ($t = t_0$), P_U is increased by ΔP ($\Delta P = 0.05 P_U$). The ensuing pressure decay in the upstream reservoir is recorded for a test period of thirty minutes.

Because the test specimen is within a closed system, P_D increases as P_U decreases until an equilibrium pressure, P_f , is reached in both the upstream and downstream reservoirs. A plot of $(P_U - P_f)$ on a semi-log scale versus time is made. The differential equation governing one-dimensional transient flow of a compressible fluid through a porous compressible medium is:

Figure 2.12

The confined sample arrangement used in transient pulse test.
(after Brace et al., 1968)

$$\frac{\partial^2 p}{\partial x^2} = \left(\frac{\mu C}{K} \right) \left[\frac{C_{eff} - C_s}{C} + n \left(1 - \frac{C_s}{C} \right) \right] \left(\frac{\partial p}{\partial t} \right) \quad (2.6)$$

where	p	=	pore pressure within the sample (kN/m ²)
	x	=	distance along the length of the test sample (m); measured from the upstream reservoir end
	t	=	time from start of test (sec)
	K	=	coefficient of permeability (m ²)
	μ	=	fluid viscosity (kN•sec/m ²)
	C	=	fluid compressibility (m ² /kN)
	C_{eff}	=	effective compressibility of the rock as measured for a jacketed sample. (m ² /kN)
	C_s	=	compressibility of the minerals in the rock. (m ² /kN)
	n	=	porosity (non-dim.)

Brace et al. (1968) found that for Westerly granite C_{eff} and C_s were both significantly less than C , therefore the first term in the square brackets of (2.6) is approximately equal to zero. Brace et al. (1968) assume that the porosity of Westerly granite is very small (as it is for most crystalline rocks). A theoretical analysis performed by Brace et al. (1968) showed that for porosities of about 0.01 the compressive storage of fluid in the pore spaces produces a transient which decays to negligible values in the short term and could therefore be neglected. They assume that for their experiments both terms in the square brackets of (2.6) can be neglected with the result:

$$\frac{\partial^2 p}{\partial x^2} = 0 \quad (2.7)$$

or

$$\frac{\partial p}{\partial x} = f(t) \quad (2.8)$$

This implies that the pressure gradient is constant along the length of the sample, but varies with time. Based on these assumptions, the pressure gradient is found to decay exponentially to zero, therefore, P_U is given by the equation:

$$(P_U - P_f) = \Delta P \left[\left(\frac{V_D}{V_U} \right) + V_D \right] e^{-\zeta t} \quad (2.9)$$

where

$$\zeta = \left(\frac{KA}{\mu CL} \right) \left(\frac{1}{V_U} + \frac{1}{V_D} \right) \quad (2.10)$$

V_U = the volume of the upstream reservoir (m^3)

V_D = the volume of the downstream reservoir (m^3)

and all other variables are as previously defined.

The slope of the $\log (P_U - P_f)$ versus time graph is $-\zeta$. Using the slope from the experimental data, equation (2.10) can be solved to obtain permeability, K .

Brace et al. (1968) pointed out several limitations of their technique. First, The

test duration is limited to approximately 30 minutes before pressure changes due to temperature and leakage begin to dominate. Second, the analysis is only valid for materials with very low porosity, C_{eff} and C_s . Third, the pressure step (ΔP) must be small since viscosity and compressibility of a fluid vary with pressure. Therefore, P_U and P_D must be reasonably close to each other so that n and C will not vary along the length of the sample. A further limitation is that it was difficult to measure small changes in pressure accurately while at high pressure.

Kranz et al. (1979) used a slightly modified version of the test set-up proposed by Brace et al. (1968) to conduct transient pulse tests to investigate the permeability of whole and jointed Barre granite. Kranz et al. (1979) used cores measuring 35 mm in diameter and 90 mm in length. Kerosene was used as the permeating fluid because it is chemically inert with respect to the minerals in this rock. The experiments were performed in a triaxial servo-controlled hydraulic press. The hollow plug used by Brace et al. (1968) was replaced by a hollow base pedestal which allowed a differential pressure transducer to be connected between the upper and lower reservoirs. The test procedure was described as closely following that of Brace et al. (1968). The pressure pulse was found to decay in time according to the equation:

$$p = P_0 e^{-jt} \quad (2.11)$$

where

$$j = \frac{KA(V_D + V_U)}{C\mu LV_D V_U} \quad (2.12)$$

and P_0 is the differential pressure between the upstream and downstream reservoirs at the commencement of the test. All others variables are as defined previously in connection with the analysis of Brace et al. (1968).

The analysis by Kranz et al. (1979) makes the same assumptions as those adopted by Brace et al. (1968), ie., Darcy's law is valid and a linear pressure gradient exists along the length of the sample.

Hsieh et al. (1981) presented an analytical solution which accounts for compressive storage of the permeant in the rock sample. The experimental procedure used by Hsieh et al. (1981) was identical to that of Brace et al. (1968). The mathematical model (the initial value problem) describing the hydraulic head in the sample and reservoirs was first presented by Lin (1977). A Laplace transform technique was used to solve the initial value problem. The solution for dimensionless hydraulic head in the upstream reservoir is:

$$\frac{h_u}{H} = \frac{1}{1 + \psi + \xi} + 2 \sum_{m=1}^{\infty} \frac{\exp(-\phi \phi_m^2)(\psi + \xi^2 \phi_m^2 / \psi)}{\left[\frac{\xi^2 \phi_m^4}{\psi^2} + \frac{(\xi^2 \psi + \xi^2 + \xi + \psi) \phi_m^2}{\psi} + (\psi^2 + \xi \psi + \psi) \right]} \quad (2.13)$$

where ϕ_m are the roots of:

$$\tan \phi = \frac{(1 + \xi) \phi}{\left(\frac{\xi \phi^2}{\psi} \right) - \psi} \quad (2.14)$$

where

$$\begin{aligned}\varphi &= \frac{k\alpha}{l^2 S_s} \\ \psi &= \frac{S_s A l}{S_u} \\ \xi &= \frac{S_d}{S_u}\end{aligned}\tag{2.15}$$

where	φ	=	the dimensionless time variable (non-dim.)
	ψ	=	the ratio of the compressive storage within the sample to the compressive storage in the upstream reservoir (non-dim.)
	ξ	=	the ratio of the compressive storage of the downstream reservoir to the compressive storage of the upstream reservoir (non-dim.)
	A	=	the cross sectional area of the sample (m ²)
	l	=	the length of the sample (m)
	S_u	=	the compressive storage of the upstream reservoir (m ²)
	S_d	=	the compressive storage of the downstream reservoir (m ²)
	k	=	the hydraulic conductivity of the sample (m/s)
	S_s	=	the specific storage of the sample (m ⁻¹)

A similar expression is given for the dimensionless hydraulic head in the downstream reservoir.

The analytical solution presented by Hsieh et al. (1981) cannot be directly used to determine the coefficient of permeability of the test material because the solution contains the permeability parameter within the summation term. Neuzil et al. (1981)

proposed a graphical method of using the analytical result given by Hsieh et al. (1981) to evaluate both k and S_r . The coefficient of absolute permeability, K , is easily evaluated from the coefficient of hydraulic conductivity, k , using equation (1.1).

Trimmer (1981) performed a parametric analysis to investigate the relationship between the systematic error from using the simplified solution proposed by Brace et al. (1968), as opposed to the rigorous numerical solution which involves finite difference techniques, and the experimental parameters (e.g. reservoir volume, fluid viscosity and compressibility, and sample properties and geometry). Trimmer (1981) generated curves of $\ln(P_U - P_f)$ versus time using both the simplified analysis given by Brace et al. (1968) (ignoring compressive storage of the fluid within the rock) and a finite difference solution of the analytical result (which accounts for compressive storage within the sample). Trimmer (1981) found that the systematic error was a function only of the ratio of effective sample pore volume to reservoir volume. The study by Trimmer (1981) found that for the systematic error to be less than 10%, the ratio of effective sample pore volume to reservoir volume must be less than 0.25.

Lin (1982) also performed a study comparing the simplified solution of Brace et al. (1968) with that of a finite difference solution. The study used the raw data obtained by Brace et al. (1968) and Kranz et al (1979). Lin (1982) found that the simplified analysis always overestimated the permeability, but that the two techniques agreed fairly well when the relative fluid storage in the sample (defined as the ratio of compressive storage in the sample to compressive storage in the upstream reservoir) was very small (less than 0.01).

Sanyal et al. (1972) presented a liquid permeameter which achieved high upstream pressures by use of a "pump" based on the thermal expansion of liquid. The samples were confined under pressure in a rubber sleeve and saturated under vacuum with hydraulic oil. A pressure gradient of approximately 11,000:1 was developed by heating of the oil in the thermal pump. The pressure decay of the upstream fluid was measured over time. A plot of $\ln [(P_i - P_o)/(P_o - P_a)]$ versus time was made. The plots are generally characterized by an initial transient decay curve followed by a linear pressure decline. The initial transient decay is attributed to compression of oil in the tubing and the pores of the rock and is not accounted for in the analysis presented by Sanyal et al. (1972). Only the linear portion of the curve is used for evaluating the permeability. The slope of the linear portion of the curve is 's' and the permeability is calculated using the equation:

$$K = - \frac{s\mu CV_i l}{A} \quad (2.16)$$

where	K	=	the coefficient of permeability (m^2)
	s	=	slope of the semilogarithmic pressure decline curve (s^{-1})
	μ	=	viscosity of the fluid (kN s/m^2)
	C	=	fluid compressibility (m^2/kN)
	V_i	=	initial volume of liquid in the "thermal pump" (m^3)
	l	=	the sample length (m)
	A	=	the cross-sectional area of the sample (m^2)

Bourbie and Walls (1982) presented a different "pulse decay " permeability test. The difference being that the pressure in the upstream reservoir is stepped up and then maintained constant at the elevated pressure. The decay of the differential pressure between the upstream and the downstream reservoirs is measured as the pressure builds up in the downstream reservoir. The analytical solution presented is similar to that given by Hsieh et al. (1981) but accounts for the slightly different boundary conditions used in the experimental set-up. Bourbie and Walls (1982) performed tests on cylindrical samples of Spirit River tight sandstone which had dimensions of 50.8 mm in diameter and 67 mm in length. Nitrogen gas was used as the permeating fluid (no mention was made of the effects on the measured permeability of using gas). To evaluate the analytical solution, Bourbie and Walls (1982) performed permeability tests on samples of the same rock using an independent steady-state technique and used these permeability results to evaluate the theoretical pulse decay. Bourbie and Walls (1982) found that the results for the theoretical pulse decay agreed very closely with the experimental results.

A similar downstream pressure build-up method was used by Freeman and Bush (1983) to determine gas permeabilities. These tests were performed at approximately 700 kPa pressure. The tests took only 200 seconds to complete and agreed to within 5% with steady-state test results.

Martin (1986) presented a method for determining the "relative permeability" of concrete using gas as the permeant. Cubes of concrete (100 x 100 x 100 mm) with a 6 mm diameter hole drilled through the centre were sealed between two steel end plates. The central hole was first pressurized to 150 psi (1,035 kPa) and then the pressure was

allowed to decay.

Martin (1986) found that the pressure (P) decay very closely approximated an exponential decay of the form:

$$\log_{10} P = 1 - qt \quad (2.17)$$

Martin concluded that q is a function of permeability but never actually determined a numerical value for the permeability. The q values were used to compare the permeabilities of one sample of concrete with another sample.

2.2.2.3 INDIRECT DETERMINATION OF PERMEABILITY

The "standard" techniques for the determination of permeability involved the measurement of pressures and/or flow rates, sometimes as a function of time. Other techniques which measure a variable which can be related to permeability (or which are at best approximate techniques) have been considered as indirect methods of determining the permeability of a material.

Rehbinder (1978) used a technique in which the average pore velocity of water flowing through a rock is measured. These tests determined the modified permeability which is a function of average pore velocity (as opposed to the filter velocity). The modified permeability is related to the intrinsic permeability by the following equation:

$$K_p = \frac{K}{n} \quad (2.18)$$

where	K_p	=	modified permeability coefficient (m^2)
	K	=	intrinsic permeability coefficient (m^2)
	n	=	porosity (non-dim.)

The short cylindrical rock sample is contained within the permeameter as shown in Figure 2.13. The sample is first saturated with pure water and at the start of the test, NaCl is introduced into the top domed reservoir until a concentration of 5% is detected by the trigger gauge. Upon detecting the 5% concentration, the trigger gauge automatically shuts the valve to the NaCl input. The electric current due to a voltage in the direction of the pressure gradient is detected by a conductor at the centre of the base plate. The pressure in the top domed reservoir is maintained at a constant 600 kPa throughout the test. Once the NaCl front has reached the bottom of the sample, a sudden drop in current will be registered. The time taken to reach this drop is labelled t_d . The modified permeability is calculated from the following relationship:

$$K_p = \frac{P_0 t_d}{\mu l^2} \quad (2.19)$$

where	K_p	=	modified permeability coefficient (m^2)
	P_0	=	reservoir pressure (kPa)
	t_d	=	time at which current drop occurs (s) (measured from the start of the test)
	μ	=	dynamic viscosity of the liquid (kN s/m^2)
	l	=	thickness of the sample (m)

1 Screw clamp, 2 O-ring, 3 Conductor, 4 Cable, 5 Connection to the release tube, 6 Connection to the supply tube, 7 Trigger gauge, 8 Rock specimen, 9 Plate of sintered bronze, 10 Plate of plexi glass, 11 Drain

Figure 2.13 Test cell used for determining the modified permeability of a porous material. (after Rehbinder, 1978)

The technique has several parameters which combine to influence the test results. The correct combination of sample geometry and test pressure must be used in order for the NaCl front to still be well defined when it reaches the bottom of the sample. A well defined front is necessary for the accurate determination of t_d . The test can produce good results, however it can be difficult to determine the precise value of t_d . Results obtained by Rehbinder (1978) for tests conducted on Stockholm Granite indicate that only eleven of nineteen tests showed a distinct sudden drop in current.

Investigators including Blair and Berryman (1986, 1987) and Schlueter et al. (1991) have developed techniques for predicting permeability (as well as electrical conductivity) of porous media from an examination of the microstructure of the porous medium. A scanning electron microscope is used to observe the arrangement of particles and void configuration in thin sections of the material. These images are then digitized by a computer and pore size and shape distributions are used to create a theoretically representative model of the real material.

3. PROPOSED EXPERIMENTAL METHODOLOGY

3.1 BASIC CONCEPT

Based on the review of existing permeability tests, it seems clear that to measure the intrinsic permeability of very low permeability materials it is desirable to use a transient test technique. It is also desirable to use a liquid as the permeating fluid. As has been discussed previously, the use of a liquid as the permeating fluid is essential in order to avoid problems attributed to the Klinkenberg effect. The transient test procedure is convenient, and in particular, avoids the long periods of time usually required to achieve steady-state flow conditions. With transient tests, the pressure is measured as a function of time as opposed to the measurement of a flow rate. This is advantageous since pressures can be measured more accurately than the extremely low flow rates that are associated with steady-state tests conducted on rocks with relatively low permeability.

The concept of the transient pulse test originally presented by Brace et al. (1968) remains relatively unchanged to date. Newer, more accurate instrumentation and computerized data acquisition systems can be used to acquire and process the transient test data with speed and accuracy. Although the transient pulse test has provided reliable results for many years, it was felt that a simpler more versatile test procedure could be developed by focussing on a test scheme which involves radial flow conditions rather than rectilinear flow.

The permeability test which is proposed in this research is a transient pulse test with radially divergent flow conditions. The proposed test would use hollow cylindrical test specimens (ie. cylindrical cores with parallel ends and a hole drilled or cored through

the centre). A nearly instantaneous pressure increase would be applied to the central cavity. The resulting pressure pulse would cause the fluid to flow radially outward. As the fluid flows, the pressure in the central cavity would decay. This pressure decay would be a function of the permeability of the test specimen. A schematic view of the proposed test configuration is shown in Figure 3.1. The axial load would be applied to the top load plate by confining the assembly in a reaction frame.

The proposed test configuration appears to offer the following advantages over the standard transient pulse test developed by Brace et al. (1968):

- 1) The equipment and test procedure could be much simpler since no confining pressure would be applied to the test specimen. This implies that there would be no requirement for a high pressure chamber or a rubber sealing sleeve.
- 2) Much smaller mechanical loads would be applied to the test specimen. The standard transient pulse test requires a confining pressure of at least 1.2 times the applied pressure in order to minimize interface flow at the boundary. Rough textured core samples sometimes require a confining pressure as high as twice the applied pressure in order to provide a seal. The proposed radial flow test would require only a sufficiently large axial load to seal an o-ring against a flat machined surface.
- 3) The geometry of the test would allow for the flexibility of testing both the permeability of intact specimens and the permeability of specimens with horizontal fractures. Figure 3.2 shows a schematic view of the proposed

test configuration involving a fractured test specimen. The only change is the test specimen itself.

The third advantage is the main impetus for developing the test using the radial flow geometry. In waste containment applications, very low permeability materials are designed to be intact so that they perform as reliable barriers to contaminant transport. The effectiveness of these barriers is open to question if for some reason cracks develop in the material. The cracks could conceivably develop due to mechanical loading or thermal stresses. The influence of fracture apertures, fracture topography, normal stresses on fractures and the flow of permeant through cracks can all have a significant effect on the effectiveness of the containment system. Although an investigation of the permeability of fractures was beyond the scope of this thesis, one of the goals was to design a test apparatus which could be easily adapted for testing both intact material and fractured material.

3.2 DESIGN CRITERIA

There were several factors which needed to be considered in the design of the experimental test facility. These factors will be briefly reviewed:

- 1) Size of Test Specimen** - The size of the test specimen dictated the dimensions of the water chamber and the accompanying reaction frame. Due to the fact that the test specimens were hollow cylinders, there was a minimum diameter which was necessary to maintain structural integrity of the test specimen while coring the central cavity and while applying the axial load to seal the central cavity. A cylinder with an outside

Figure 3.1 Schematic view of the proposed test configuration.

Figure 3.2 Schematic view of the proposed test configuration used to test the permeability of fractured material.

diameter of 75 mm and an inside diameter of 10 mm was considered to be a reasonable lower limit for the specimen size. The upper size limit governed the design of the apparatus. Due to the interest in the determination of the permeability of concrete and availability of test specimens, it was desirable to be able to use standard concrete cylinders, which are 150 mm in diameter and 300 mm in length. The upper limit on specimen size that the apparatus would need to be able to handle was therefore set at 150 mm outer diameter by approximately 25 mm inside diameter. The maximum length of the test specimens was set at 250 mm. Consequently, the ends of standard concrete cylinders needed to be trimmed. With the specimen sizes chosen above, the sample weight was not a problem with regard to installing and handling the test specimens.

The size of the test specimen also had an influence on the pressure which was used in the test procedure. Appendix A shows calculations which were performed to ensure that the pressure in the central cavity would not cause a tensile failure of the test specimen.

2) **Ease of Use** - The test equipment should have a simple configuration. As with almost all engineering test equipment, it was not possible to eliminate specialized equipment from the test set-up, however, the design led to a test which is easy to perform. The investigator performing the tests requires only a minimum of skill or practice in order to obtain consistent results.

3) **Versatility** - The test equipment was to be designed with the ability to test both intact and fractured materials. The analysis will require modifications to account for the flow through the fractures and the pressure supply may need to be changed to

accommodate increased flow rates but any modifications to the test equipment should be minimal.

4) Material Compatibility - For long term durability of the experimental equipment it was necessary for those components of the equipment which would come into contact with the permeating fluid and/or the test specimens to be made of a material which would not react chemically with the permeating fluid and/or the test material.

3.3 PROPOSED DESIGN

The proposed permeability device has three main components in the experimental set-up: these are the test specimen assembly, the pressure supply, and the data acquisition system. A schematic view of the experimental set-up is shown in Figure 3.3 and a photograph of the set-up is shown in Figure 3.4. The pressure supply and the data acquisition system were selected from commercially available components and will be described in subsequent sections of this chapter. The *test specimen assembly* was the component which required adequate design and which makes this permeability test unique.

3.3.1 TEST SPECIMEN ASSEMBLY

The test specimen assembly consists of three main components: the water chamber, the top load plate, and the reaction frame. All components of the assembly which come into direct contact with the permeating fluid and/or the test material were fabricated from stainless steel. This should ensure long term durability of the apparatus

Figure 3.3 Schematic diagram of the experimental test set-up.

Figure 3.4 Photograph of the experimental set-up for the radial-flow transient pulse permeability test.

and resistance to reactions with the permeating fluid and/or test material.

The stainless steel water chamber has an inside diameter of 292 mm and a depth of 305 mm. The wall thickness is 6.4 mm. The volumetric capacity of the chamber is 20.4 litres. The size of the chamber is sufficient for testing specimens as large as 150 mm in diameter and 250 mm in length. The chamber is much larger than the test specimens in order to provide for an unrestricted work space during the positioning of the specimen. Stainless steel flanges were welded on at the top and bottom of the stainless steel tube which forms the wall of the water chamber. The top flange of the chamber has an O-ring groove in it so that a top plate or lid can be sealed against it to transform the water chamber into a vacuum chamber. The bottom flange rests on an O-ring which sits in a groove in the bottom plate. Four bolts, evenly spaced around the circumference, pass through the flange and thread directly into the bottom plate. These can be tightened to form a seal. A cross-sectional view of the water chamber is shown in Figure 3.5. Figure 3.6 shows a photograph of the test set-up during the vacuum saturation phase of the test.

The base of the water chamber is a stainless steel plate 400 mm by 460 mm by 12.7 mm which has been machined smooth over the entire top surface. There are two O-ring grooves in the top surface of the plate; the one which provides the seal against the bottom flange of the water chamber and a 50.7 mm outside diameter groove around the centre to provide a seal between the plate and the test specimen. In order to measure the pressure in the central cavity of the test specimen, a hole has been drilled and tapped through the centre of the bottom plate. An adapter is used to connect the pressure

Figure 3.5 Cross-sectional view of the water chamber.

Figure 3.6 The experimental test set-up during vacuum saturation of the test specimen.

transducer to the base plate. This allows for different styles of transducers to be used by changing the adapter instead of having to modify the base plate. The adapter seals against the underside of the base plate via an O-ring. To provide a smooth surface for this O-ring to seal against, the bottom of the base plate has been machined smooth over a 50 mm radius from the centre.

The top loading plate serves both as a rigid loading head against which the test specimen is sealed and as the manifold for the fluid pressure inlet to the specimen cavity and the bleeder port. It was designed to fit precisely on the top of a 150 mm diameter test specimen, but can also be used with samples of smaller diameter. The top loading plate is 150 mm in diameter and 25 mm thick. Two flattened areas have been made at the edge of the plate. The flattened areas are oriented 180° from each other and provide areas for the connection of fittings. Two holes were drilled in the plate; one at mid-height of the plate from the centre of one flattened area through to the centre of the other flattened area and the second hole upwards from the centre of the base to intersect the cross-drilled hole. A plan view and a cross-sectional view through the middle of the plate are shown in Figure 3.7. The ends of the cross-drilled hole were tapped and machined to conform to an 7/16-20 SAE/MS internal straight thread boss. Stainless steel SAE/MS positionable male elbows were then attached. The positionable elbows have O-rings which seat against the bosses to provide the seal. Swagelok tube connectors are on the opposite end of the elbows. One elbow is connected to a Nupro plug valve which seals in the fluid pressure, while the other elbow has a plug cap which serves as a bleeder valve. A depression was machined in the centre of the top face of the loading plate.

Note: All measurements in millimetres

Figure 3.7 Plan view of top load plate and cross-sectional view through the centre of the plate.

The load is applied by the reaction frame through a 26 mm diameter hardened steel ball bearing which rests in the depression. This configuration helps to ensure that the load is applied axially through the centre of the test cylinder. The reaction frame consists of a rigid base, two threaded rods and a rigid top beam. The rigid base was originally designed and built for use in the experimental set-up of an unrelated research project. The base was fabricated by welding steel plates that are 600 mm by 600 mm by 25 mm with a central hole 225 mm in diameter to the top and bottom of 100 mm long piece of steel pipe. The steel pipe had an inside diameter of 225 mm and an outside diameter of 250 mm. The bottom plate of the water chamber sits over top of the hole in the rigid base so that the pressure transducer protrudes into the hole. To provide access for the leads from the pressure transducer to the data acquisition board, four holes were drilled in the corners on the bottom plate of the rigid base and aluminum cylinders attached to provide a clearance of 100 mm. The reaction frame was shown in Figure 3.3.

The plates which form the top and bottom of the rigid base both had 8 evenly spaced 27 mm diameter holes drilled through them on a radius of 241 mm. Two 1"-8 UNC threaded rods, 900 mm in length, were attached to the top plate of the rigid base by passing them through two of the existing holes which are located 180° from each other. Two nuts, one on each side of the plate, were used to lock the rods in position.

The top load beam was fabricated by welding 76.2 mm by 610 mm by 12.7 mm strips of steel onto the top and bottom sides of a 76.2 x 101.6 x 6.35 hollow structural section. Four 50 mm long fillet welds were used for each steel strip. Holes were drilled straight through the entire beam from top to bottom so that the beam could fit over the

two threaded rods. A smaller hole was drilled through the bottom of the rigid beam at the midpoint between the two ends. A bolt was passed through the small hole from the inside of the hollow beam and threaded into a 95 mm long rod which was 50 mm in diameter. The rod served as a spacer to apply the axial load to test specimens which sit below the top flange of the water chamber. A load cell was attached to the bottom of the 50 mm diameter rod. The base of the load cell had a dimpled load head which rested on the 26 mm diameter ball bearing.

3.3.2 PRESSURE SUPPLY

Tap water was used as the permeating fluid. A constant pressure apparatus was used to provide the water pressure to the central cavity in the test specimen. The constant pressure apparatus is an EL27-432 series model produced by Engineering Laboratory Equipment Limited of England. The apparatus maintains a constant pressure by balancing a 'deadweight' load on a frictionless spindle against a column of oil operating under continuous feed back conditions. The constant pressure apparatus has a pressure range between 100 kPa and 3500 kPa and can be varied in increments of 20 , 40, 100 or 300 kPa.

3.3.3 DATA ACQUISITION SYSTEM

Three sets of data were recorded throughout each test: these include the pressure in the central cavity of the test specimen, the axial load acting at the top of the test specimen, and the temperature of the water in the water chamber.

The temperature of the water was measured with a type K thermocouple which was submerged in the water bath. The sensing tip of the thermocouple wire was kept at least 25 mm from the wall of the chamber and from the specimen. The type K thermocouple was made by tig welding a junction between an alumel and a chromel wire. The junction was then insulated from the water with several layers of Devcon liquid aluminum epoxy. The pressure in the central cavity of the test specimen was measured using a DCT Instruments PZA100AC series port style pressure transducer. The manufacturer's specifications are:

Pressure range:	100 psia (700 kPa) (pressure is measured with reference to a vacuum)
Input excitation:	10 VDC
Output signal:	5 mV/V
Linearity and hysteresis:	0.50% of full scale
Temperature range:	
Compensated	70 to 170 °F (21.1 to 76.7 °C)
Operating	0 to 180 °F (-17.8 to 82.2 °C)
Safe overload:	200% of full scale
Calibration factor:	20.1557 mV/V

The transducer was purchased with a calibration certificate from the manufacturer. This calibration factor is accepted at face value since the laboratories at Carleton University do not have the facilities to accurately calibrate such a pressure transducer over its entire range. A rough check of the calibration was made by comparing the pressure

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

transducer reading to the pressures set by the constant pressure apparatus. These experiments confirm the manufacturer's calibration data over the pressure range 0-700 kPa.

The load cell used to measure the axial load provided a means of ensuring that the load applied to seal the top load plate against the test specimen was consistent for all tests. The load cell can also be useful for tests on crack permeability measurement. The effect of axial load on the crack permeability could be investigated. The load cell is an Interface model 1210-AF with a capacity of 10,000 lbs (44.5 kN). The manufacturer's specifications are:

Capacity:	10,000 lbs (44.48 kN)
Input excitation:	10 VDC
Output signal:	5 mV/V
Temperature range:	
Compensated:	15 to 115 °F (-9.4 to 46.1 °C)
Operating:	-65 to 200 °F (-53.9 to 93.3 °C)
Static error band:	+/- 0.05 % of full scale
Non-linearity:	+/- 0.05 % of full scale
Safe overload:	150 % of rated range
Calibration factor:	4.193 mV/V

The computerized data acquisition system which was used was a commercially available package from National Instruments Corporation and consisted of an AMUX-64T

analog multiplexer with temperature sensor, an AT-MIO-16F-5 data acquisition board which plugged directly into a slot in a 486DX33 PC computer installed with the LabWindows software package. The software package allowed the data acquisition program to be custom designed. The program displayed the time history of both the axial load and the pressure, but recorded all three sets of data (temperature, load and pressure) at time intervals prescribed by the user.

The signal leads from the thermocouple wire, pressure transducer and load cell were all attached to the analog multiplexer which in turn transmitted the signals to the data acquisition board. The pressure transducer and load cell both needed an excitation voltage of 10 VDC which was provided by connecting the power leads to a DC power supply box.

3.4 VALIDATION PROCEDURE

The principal assumption made in the experimental methodology of the proposed permeability test was that all pressure decay in the central cavity is due to flow of the pressurized fluid radially outward through the porous test specimen. Tests were performed to confirm the validity of this assumption. The validation test procedure is described in the following paragraphs.

If the assumption that all pressure loss is due to the flow of pressurized fluid through the porous test specimen is correct, no pressure drop should be observed if the test specimen is impermeable. If an impermeable test specimen is tested and a pressure drop is observed, it can be concluded that factors other than the permeability of the test

material and the fluid properties are influencing the permeability test results. The other factors would likely be leakage from the seals, valves and/or fittings.

An impermeable test specimen was fabricated by machining a hollow cylinder from a solid rod of aluminum which was 114.3 mm in diameter. The end faces were machined smooth and parallel in a metal lathe. The final dimensions are 113 mm outside diameter by 25.4 mm inside diameter by 150.8 mm in length.

The validation test procedure is best described in a generic form since small details of the experimental design changed as part of the iterative design process. The changes were based on analysis and interpretation of the validation test results. The validation test was essentially the evaluation part of the design cycle. The sequence of the tasks associated with the validation test procedure can be 'generically' described as follows:

- 1) The water chamber was filled half-way with water.
- 2) The aluminum specimen was placed in the water chamber and positioned so that it was centred over the pressure transducer in the base plate.
- 3) The chamber was filled with water so that the top of the aluminum specimen was covered by at least 60 mm of water.
- 4) The vacuum lid was placed over top of the water chamber and a vacuum applied for approximately 2 hours.
- 5) The top plate was positioned on top of the aluminum specimen with the valve and bleeder cap open. (It was fully submerged.)
- 6) A vacuum was then applied for 1 hour.

- 7) The axial load of 5000 N was applied to the specimen through the top loading plate by tightening down the load frame.
- 8) All the tubes and the top load plate were then flushed with water to remove any trapped air bubbles.
- 9) The bleeder cap was closed and the cavity in the aluminum specimen was then pressurized to 600 kPa and sealed (ie. the inlet valve is closed).
- 10) The pressure within the cavity was monitored by the computer data acquisition system and readings recorded every 5 minutes for a period of 3 hours.

3.5 DESIGN REFINEMENT

The effectiveness of the proposed design was evaluated using the validation test procedure described in section 3.4. The pressure response obtained in this test is shown in Figure 3.8. The figure shows a significant and continuous decay in the pressure, likely indicating the presence of a very small leak in the system. The test was repeated several times with similar results.

The procedure for finding and eliminating the small leak was a difficult process of trial and error. The fact that the leakage could be either due to a single small leak or a series of very small leaks made the process even more difficult. The potential sources of leakage and other factors which could result in a pressure decline were identified as follows:

- a) Improperly tightened seals and connections
- b) Thermally induced expansion of the pressurized cavity

Figure 3.8 Pressure response from validation test on the proposed design, shown in dimensionless form.

- c) Relaxation of the axial load which provides the force for sealing the load plate against the top of the test specimen.
- d) Poorly machined sealing surfaces
- e) Quality of seals provided by properly installed valves and connections

In order to confirm that the leakage was not through the connections and sealing parts, these components were dismantled, cleaned and reassembled. The validation procedure was repeated but nearly identical pressure responses were recorded. The data from the thermocouple and the load cell was also examined for variations which could have caused a pressure drop. Throughout the duration of the test, the temperature in the water bath was found to be constant. Small decreases in the axial load measured by the load cell were observed. To verify if the decrease in the load could result in the pressure decay, the threaded rods were tightened in order to restore the axial load to its original value. A negligible change in the pressure was observed during this operation, indicating that the pressure decay was not a consequence of the loss of axial load. It was therefore concluded that the pressure decay must result from leakage in the seals, valves and/or fittings.

A detailed inspection of all of the seals, fittings and valves revealed that the threaded holes in the sides of the top load plate had not been fabricated as per the design specifications (the design specifications called for a 7/16-20 SAE/MS internal straight thread boss). However, the opening to the holes had simply been chamfered. The chamfer did not provide the appropriate sealing surface and containment required for the

O-ring on the male positional elbow. As a result, the O-rings were pinched between the flanges on the elbows and the edge of the chamfers, resulting in damage to the O-rings). It was not possible to remachine the top load plate to conform to the original design. An unsuccessful attempt was made to salvage the positional elbows by machining a deeper chamfer in the load plate and installing new O-rings. This alteration did not result in any improvements in the pressure response.

The male positional elbows were replaced with elbows which connected to the plate by a 1/4" NPT pipe thread. This required that the holes be drilled out to a larger diameter and tapped to accommodate a 1/4" NPT pipe thread fitting. One of the elbows could not be tightened into place because the hole in the plate had been tapped too deeply (a pipe thread fitting has tapered threads and seals itself in place when its threads lock against the threads in the hole - when the hole is tapped too deeply, there is insufficient taper left in the threaded hole to cause the threads to lock against each other). Before a tight seal between the threads could be reached the flange at the base of the threads on the elbow locked against the side of the load plate. A proper seal could not be guaranteed with this connection.

A reliable connection was eventually achieved by welding the elbows into position. This task was performed at the Science Technology Center at Carleton University. The machinist oriented the elbows in the appropriate direction then tig welded around the full circumference of the thread. The machinist also noticed that the O-ring groove at the base of the load plate was not machined to conform to a proper sealing surface. He indicated that this could be a contributing factor to the leakage and

the associated pressure drop. As a result of this observation, the bottom surface and the O-ring groove were remachined. The results from the validation test still showed a pressure decay but with less severity. This improvement indicates that the observed pressure decay was a result of more than one source.

The quality of the seals provided by the valves and tube connectors was investigated. The Nupro plug valve was rated for pressures of 20,685 kPa (3,000 psi) but was not leak tested by the manufacturer. The Swagelok tube fittings are not leak tested but were expected to be 100% leak free. Discussions with suppliers revealed that valves and fittings often have what is referred to as "dead space" or "dead volume". The dead space usually exists around the sealing components of the valve or fitting and is initially filled with air. This air becomes sealed in the upstream side of the flow when the seal is closed. The dead space can cause a "virtual leak". A "virtual leak" occurs when, over a period of time, the fluid under pressure seeps into the dead space until it becomes filled. Once the dead space is filled, the fluid travels no further, therefore no fluid would be detected as leaving the system. In a pressure sensitive test such as the one used here, a pressure decay could result from the increase in volume which the water occupies. A new valve with a lower leakage rate and a relatively small dead space was installed. The valve was a Whitey severe service union bonnet valve rated for 41,370 kPa (6,000 psi) pressure and with a tested leakage rate of less than 0.1 cm³/min of nitrogen at 6,800 kPa. The validation procedure was repeated and the results showed an initial drop in pressure over the first few minutes of the test followed by a relatively constant pressure state. The results from three validation tests performed using this set-up are shown in Figure 3.9.

It was concluded that the pressure decay which occurred within the initial portion of the test could be ignored since this drop would be substantially smaller than the pressure drop which would be observed in tests conducted on porous media.

3.6 TEST SPECIMEN PREPARATION

In order to provide a full seal between the test specimen and the bottom and top plates, it was necessary for the end surfaces to be flat and parallel. In order to ensure radial flow conditions, it was also necessary to seal the ends of the test specimens. The test specimen preparation technique was developed by a series of trial and error investigations of different techniques on cast grout cylinders.

The first attempts at sealing the end faces consisted of using gaskets made out of very thin latex (cut from triaxial membranes), 1/16" thick neoprene and 1/8" thick neoprene. The gaskets were cut to cover the entire end surface of the test specimens and were placed between the test specimen and the top and bottom plates. The gaskets were used in conjunction with the O-rings which were housed in the plates. These materials were found to be unsatisfactory; in fact, the use of a gasket was deemed to be a poor choice to provide a seal between a smooth metal face and the porous face of the test specimens. It was decided that the ends of the test specimens should be sealed against water flow by a sealant which would fill in the open pores of the specimen face. An assortment of epoxies and sealing adhesives were evaluated for use in sealing the end faces of the test specimen and for attaching machined stainless steel plates to the ends. An O-ring was then used to seal between the top and bottom plates of the test apparatus

Figure 3.9 Pressure response, in dimensionless form, from validation tests on the final experimental design.

and the stainless steel end plates on the test specimen. A summary of the epoxies and sealing adhesives used in the research programme is shown in Table 3.1 .

The Bondo Marine Resin was found to give a good seal which would perform well under the exposure to pressure and water influx conditions. In the following, the procedure for attaching the stainless steel end plates to the grout cylinders is described:

- 1) The ends of the stainless steel end plates which were to be epoxied to the test specimen were first roughened on a belt sander and wiped clean with acetone.
- 2) The test specimen was stood on one end and the top end surface was wiped clean with acetone.
- 3) The Bondo Marine Resin was mixed with the liquid hardener as per manufacturer's instructions and applied evenly to the top surface of the test cylinder. The entire end surface was covered with a layer of resin about 2 mm thick (the resin had the consistency of syrup).
- 4) A lesser amount of resin was applied to the surface of the stainless steel end plate and spread around so that just a thin film of resin covered the entire surface area.
- 5) Approximately 10 minutes was allowed for the resin to thicken and to soak into the porous specimen.
- 6) The test specimen was then flipped upside down and placed on top of the stainless steel end plate. The two surfaces to which the resin was applied were pressed together.
- 7) A 10 kg weight was placed on the top end of the test specimen in order to maintain good contact pressure while the resin set.
- 8) The specimen was left to set for a period of 3 hours after which the opposite end

Trial	Epoxy	Performance
1	Lepage Industrial 5 Minute Epoxy	<ul style="list-style-type: none"> • lifted away from grout surface • easily peeled off of stainless steel end plates
2	Lepage Industrial 24 Hour Epoxy	<ul style="list-style-type: none"> • lifted away from grout surface after several days exposure to water and test pressures • easily peeled off of stainless steel end plates
3	Loctite Depend	<ul style="list-style-type: none"> • blistered away from grout surface and eventually led to leakage • difficult to ensure uniform application • strong bond
4	Seal-All Adhesive	<ul style="list-style-type: none"> • very strong bond but leaked • does not apply to surfaces smoothly, therefore gaps in the interface
5	Bondo Marine Resin	<ul style="list-style-type: none"> • provided strong, durable seal and bond <i>provided</i> both surfaces are properly cleaned before bonding

Table 3.1 Summary of adhesives and sealants which were evaluated for attaching and sealing the stainless steel end plates to the grout cylinders.

of the specimen was prepared in the same manner.

- 9) A period of 24 hours was allowed for full curing before the specimens were exposed to water.

3.7 EXPERIMENTAL PROCEDURE

The experimental procedure which was followed in performing the transient pulse tests with the equipment developed is described in the ensuing paragraphs.

- 1) The test specimen was vacuum saturated with water. The vacuum pump was connected to an on-off timer switch. The switch turned the pump on for 30 minutes then shut it off for 30 minutes, then repeated this cycle. The on-off cycle was operated for a period of 96 hours.

The sample was then transferred to the test chamber, which was already filled with water, and positioned in the centre so that the pressure transducer in the bottom plate was exposed to the water in the central cavity of the test specimen. The top plate was then placed on the top of the specimen and the valve and bleeder cap disconnected and placed in the chamber along with the specimen. At this point, the specimen, the valve and the plug were all submerged in water. The water level in the chamber was adjusted so that it was approximately 25 mm below the top of the chamber. The vacuum lid was placed over top of the chamber and a vacuum was applied for a period of 4 hours.

- 2) While in a submersed condition, the valve and bleeder plug were connected to the top plate. This was done to try to prevent any air bubbles from being trapped in the fittings. The valve was in the open position at this stage.

- 3) The water level was then lowered to mid-height of the top plate. This was done by syphoning with a 6.4 mm inner diameter plastic tube.
- 4) The 26 mm diameter ball bearing was placed in the depression in the centre of the top plate.
- 5) The computer that was used for data acquisition and the data acquisition program were activated. The name of the data file was entered and the load cell and pressure transducer readings were set to zero.
- 6) The load head was lowered onto the ball bearing and any minor adjustments in specimen positioning were made. The load head was tightened down using the nuts on the two threaded rods. The nuts were tightened as evenly as possible by tightening one nut by a fraction of a turn, then the other nut by an equal amount. The nuts were tightened until an axial load of 5000 N was registered by the load cell. The specimen was then left overnight to allow for the dissipation of any excess pore pressures. Excess pore pressures would be developed in the grout upon application of the axial load.
- 7) The plastic tube from the constant pressure apparatus was bled of any air bubbles and then connected to the valve.
- 8) A small pressure (approximately 100 kPa) was applied to the cavity of the specimen, and the bleeder plug was opened to flush the system.
- 9) The bleeder plug was tightened and a pressure of 600 kPa was applied to the cavity. It took approximately 10 seconds for the constant pressure apparatus to build up to a constant pressure of 600 kPa.

- 10) As soon as a steady reading of 600 kPa was established, the valve was closed and the data acquisition was commenced. Readings of the pressure in the cavity, the axial load and the water temperature were all recorded. The first set of readings were recorded as soon as the start button was pressed. The next set of readings was taken after 30 seconds, and the intervals of subsequent readings was set at every 300 seconds.
- 11) The data acquisition was stopped after 3 hours. At that point, the bleeder plug was opened and the specimen was left overnight to allow all remaining excess pore pressures to dissipate.
- 12) The test was repeated two more times from step 8 onwards. This gave three sets of results on the same specimen under the same conditions.

4. THEORETICAL MODELLING

4.1 PROBLEM DEFINITION AND BASIC ASSUMPTIONS

The experimental configuration represents a problem of transient radial flow from a pressurized borehole of radius ' a ' which is located in a saturated porous medium. Several assumptions are made in the development of a theoretical model of the test configuration.

- 1) It is assumed that the porous medium is fully saturated and that the flow of the permeating fluid in the porous medium is governed by Darcy's Law.
- 2) It is also assumed that the solids comprising the porous medium are incompressible, therefore the porosity of the porous medium is influenced only by the bulk compressibility of the medium.
- 3) It is further assumed that isothermal test conditions exist and that the permeating fluid has a known compressibility which is constant throughout the pressure range of the tests.

The assumption that the borehole is in a medium of infinite radial extent is made in order to greatly simplify the theoretical development. The validity of this assumption has been investigated by Selvadurai (1994). It can be shown that if the ratio of the diameter of the test specimen to the diameter of the central cavity is greater than 5 there will be virtually no difference between the solutions obtained using the finite radial geometry configuration and the result involving a porous medium of infinite extent. This assumption is valid for a wide range of material parameter combinations encountered in the problem.

4.2 GOVERNING EQUATIONS

By considering both Darcy's Law and the equations of continuity it can be shown (Fetter, 1988) that the differential equation governing the transient head distribution within the pores of a medium due to pressurization of a borehole is given by:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{S}{T_R} \frac{\partial h}{\partial t} \quad (4.1)$$

This relationship can be expressed in terms of the pore pressure, p , as follows:

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} = \frac{S}{T_R} \frac{\partial p}{\partial t} \quad (4.2)$$

where 'S' is the storage coefficient of the test specimen, defined by

$$S = l \gamma_w [n C_w + C_{eff}] \quad (4.3)$$

- where
- l = length of the test specimen (=length of central cavity) (m)
 - γ_w = unit weight of water (kN/m³)
 - n = porosity of the porous medium (non-dim.)
 - C_w = compressibility of water (m²/kN)
 - C_{eff} = bulk compressibility of test specimen (m²/kN)

In (4.1) and (4.2), T_R is the transmissivity of the borehole, and is defined by

$$T_R = k l = \frac{K l \gamma_w}{\mu} \quad (4.4)$$

- where
- k = hydraulic conductivity of the porous medium (m/s)
 - K = permeability of the porous medium (m²)

μ = absolute viscosity of the permeating fluid (kN s/m²)

The initial and the boundary conditions for the radial-flow transient pulse permeability test are as follows:

$$p(r,0) = 0 \quad (4.5)$$

$$p(\infty,t) = 0 \quad (4.6)$$

$$p(a,t) = P(t) \quad (4.7)$$

$$P(0) = P_o \quad (4.8)$$

$$2\pi a T_R \left[\frac{\partial p(t)}{\partial r} \right]_{r=a} = V_w C_w \gamma_w \frac{\partial P(t)}{\partial t} \quad (4.9)$$

where $p(r,t)$ = pore pressure (kN/m²)

$P(t)$ = fluid pressure in the central cavity (kN/m²)

The boundary condition (4.5) states that at the start of the test, the pressure throughout the entire sample is equal to zero. The boundary condition (4.6) states that at an infinite radial distance from the cylindrical cavity the pressure remains equal to zero throughout the entire test, regardless of the magnitude of the pressure in the cylindrical cavity. The boundary condition (4.7) states that the pressure within the borehole is a time dependent variable and that the pore pressure in the porous medium at the face of the borehole is equal to the pressure in the borehole at all times. The boundary condition (4.8) implies that the pressure within the borehole is a constant at the start of the test

($t=0$). The boundary equation (4.9) states that the rate at which water flows from the pressurized cavity into the surrounding porous test sample is equal to the rate at which water stored within the pressurized cavity expands as the pressure within the system declines. In (4.9), V_w refers to the volume of the pressurized section of the test system including the cylindrical cavity in the specimen and water pathways in the bottom plate and load head. It is assumed that the volume of the pressurized test section is constant throughout a test.

The solution of (4.2) subject to the initial and boundary conditions (4.5) to (4.9) has been studied in detail in connection with non-steady ground water flow (Bredehoeft and Papadopoulos (1980), Cooper et al. (1967) and Papadopoulos et al. (1973)) and in connection with the analogous heat flow problem (Carslaw and Jaeger, 1959).

Avoiding details of the analysis, which is well documented in the above studies, the decay of pressure within the pressurized cavity can be expressed in the form:

$$\frac{P(t)}{P_0} = F(\alpha, \beta) \quad (4.10)$$

where

$$\begin{aligned} \alpha &= \frac{\pi a^2 S}{V_w C_w \gamma_w} \\ \beta &= \frac{\pi T_R t}{V_w C_w \gamma_w} \end{aligned} \quad (4.11)$$

and where the function $F(\alpha, \beta)$ can be expressed in the integral form

$$F(\alpha, \beta) = \frac{8\alpha}{\pi^2} \int_0^\infty \frac{\exp(-\beta u^2/\alpha)}{u f(u, \alpha)} du \quad (4.12)$$

where

$$f(u, \alpha) = [u J_0(u) - 2\alpha J_1(u)]^2 + [u Y_0(u) - 2\alpha Y_1(u)]^2 \quad (4.13)$$

and $J_0(u)$, $J_1(u)$, $Y_0(u)$ and $Y_1(u)$ are zero order and first order Bessel functions of the first and second kind respectively. Tabulated values for $F(\alpha, \beta)$ are given by Cooper et al. (1967), Papadopoulos et al. (1973), and Bredehoeft and Papadopoulos (1980) [See Appendix B]. A useful approximation for $F(\alpha, \beta)$ was presented by Bredehoeft and Papadopoulos (1980) in the form

$$F(\alpha, \beta) = e^{4\alpha\beta} \operatorname{erfc} [2\sqrt{\alpha\beta}] \quad (4.14)$$

where erfc is the complimentary error function, tabulated values of which are given by Fetter (1993). A further approximation can be used to evaluate $\operatorname{erfc}(z)$:

$$\operatorname{erfc}(z) = 1 - \frac{2}{\sqrt{\pi}} \left(z - \frac{z^3}{3 \cdot 1!} + \frac{z^5}{5 \cdot 2!} - \frac{z^7}{7 \cdot 3!} + \dots \right) \quad (4.15)$$

Bredehoeft and Papadopoulos (1980) have shown that (4.12) and (4.14) give virtually identical results for values of $\alpha > 10$, but for values of $\alpha < 10$ tabulated values for (4.12) should be used.

4.3 APPLICATION OF THE THEORETICAL MODEL

The theoretical model describes the dimensionless pressure response within the pressurized cavity. The experimental procedure yields data describing the pressure decay within the pressurized cavity. The permeability of the test material can be determined by comparing the experimental pressure response to a set of theoretical responses evaluated for different values of permeability.

First, the experimental data for pressure within the cavity must be converted to a dimensionless form in order to match the equivalent results derived from the theoretical model. This is done by normalizing the pressure decay data with respect to P_o , the cavity fluid pressure at the start of the test.

The dimensionless parameter α depends on the geometry of the test sample and of test apparatus, as well as the material properties of the test sample and the permeating fluid. The α parameter is therefore independent of pressure and time and can be taken as a constant for the test system. The dimensionless parameter β is a function of geometric and material property constants as well as a time variable t . One of the material property constants which is included in β is the material permeability K . Therefore, for a selected value of K , the dimensionless pressure, $F(\alpha, \beta)$, can be evaluated as a function of time.

The most efficient way to evaluate the theoretical dimensionless pressure decay curve is to set up a spreadsheet on a computer. If the dimensionless parameter α is greater than or equal to 10, the approximations given by equations (4.14) and (4.15) can be used to evaluate $F(\alpha, \beta)$ for user selected values of time. All the calculations can be

performed using the computer spreadsheet. If the dimensionless parameter α is less than or equal to 10, tabulated values of $F(\alpha, \beta)$ should be used. The tables give $F(\alpha, \beta)$ for a wide range of β values from 0.000001 to 1000 at specific values of α . Bredehoeft and Papadopoulos (1980) give a table for $\alpha = 0.1, 0.2, 0.5, 1, 2, 5$ and 10 while Cooper et al. (1967) and Papadopoulos et al. (1973) give tables which cover ten orders of magnitude of α from $\alpha = 10^{-10}$ to $\alpha = 10^{-1}$. Since α is a system constant, the values of $F(\alpha, \beta)$ can be interpolated from the available tables and the corresponding time t calculated from β for a selected value of the permeability.

The series of theoretical pressure decay curves are all plotted on the same graph along with the experimental pressure decay curve. The permeability of the test material is determined by comparing the experimental curve with the theoretical results and either finding a match or alternatively interpolating between the theoretical curves.

5. EXPERIMENTAL PROGRAM

5.1 GENERAL

A series of transient pulse tests were carried out on three grout cylinders. The purpose of these tests was to demonstrate that consistent results could be obtained by using the experimental facility, the test procedure and the analysis technique presented in this thesis. This chapter will describe the fabrication process and material properties of the test specimens chosen for this testing program. The results from the experimental program will be presented along with the theoretical predictions. Observations made during the testing and the ensuing comparisons with the theoretical predictions will be noted.

5.2 TEST SPECIMENS

In order to demonstrate the consistency of a test, it is necessary to establish that any differences in the test results are due to real differences in the hydraulic conductivity properties of the material being tested. Therefore, if multiple tests are carried out on the same sample, the results should be the same, and if different samples of the *same* material are tested, the results should be the same. Based on this reasoning, it was decided that it would be desirable to have test specimens with "theoretically" identical material properties. Cast grout cylinders were chosen for use as the test specimens since it was far easier to produce a set of grout cylinders with similar properties. Within the scope of the project, the testing of rock cores was possible. Unfortunately, due to limitations of time, this aspect is relegated to further studies.

5.2.1 TEST SPECIMEN FABRICATION

For the purposes of the experimentation, a batch of ten 150 mm diameter by 300 mm long grout cylinders were fabricated. Six 20 kg bags of Sika 212 grout mix were mixed in a portable drum mixer as per instructions of the supplier (4 litres of water per bag of grout). The grout was scooped from the drum mixer and poured into the cylinder molds. Once the cylinder molds were filled, the sides of the molds were tapped gently several times in order to ensure that any large air voids collapsed. Any excess grout was scraped off of the top of the molds. Six cylinders with dimensions of 75 mm in diameter and 150 mm in length were also fabricated. The cylinders were then covered with damp rags and two bowls with steaming hot water were placed beside them on the ground. A plastic tarp was then placed over top of the cylinders and weighted down. After a period of twenty-four hours, the cylinders were stripped from their molds and transferred to the curing room and left to cure for 28 days.

After the 28 day curing period, the cylinders were removed from the curing room and a 10 mm slice was cut off the top end of each cylinder with the masonry saw. This provided a smooth surface into which coring could commence. It was found that if the surface was rough, the coring bit vibrated severely and gave a very rough start to the formation of the central cavity. All of the cylinders were then cored out with a one inch nominal diameter diamond tooth coring bit. The cylinders were cored out straight through the centre, from end to end, and the cores were kept as specimens for measurement of void ratio.

Both ends of the cylinders were then cut off with the masonry saw so that the

cylinders were approximately 235 mm long. The ends were then ground smooth and parallel with a concrete cylinder grinder available at the Civil Engineering Laboratories at McGill University. The finished test cylinders were 225 mm in length and 152 mm in diameter with a central borehole 26 mm in diameter.

The finished test cylinders were then ready to be fixed with the stainless steel end plates using the epoxy adhesion procedure described in section 3.7.

5.2.2 MATERIAL PROPERTIES OF THE GROUT SPECIMENS

The theoretical developments outlined in Chapter 4 require the use of constitutive parameters, such as compressibility of the unsaturated grout (C_{eff}), and physical parameters such as the porosity of the material (n). In order to evaluate the compressibility of the porous grout skeleton it is necessary to determine the Young's modulus (E) and the Poisson's ratio (ν) of the material. These material properties can be accurately measured using test procedures outlined in ASTM standards.

The porosity of the grout was determined by performing void ratio tests in accordance with ASTM C 642-82. The cylindrical samples recovered from the coring of the test cylinders were used for this purpose. The porosity is related to the void ratio (e) of the material through the relationship:

$$n = \frac{e}{1+e} \quad (5.1)$$

where n = porosity (non-dim.)

e = void ratio (non-dim.)

Three grout cylinders measuring 75 mm in diameter and 150 mm in length were used for determination of Young's modulus and Poisson's ratio. Two strain gauges were mounted at mid-height of each cylinder. The strain gauges were Showa model N11-FA-8-120-11 gauges with a gauge length of 8 mm. One strain gauge was oriented in the longitudinal direction and the other in the circumferential direction. The ends of the cylinders were capped with sulphur capping compound in order to provide flat and parallel ends. The cylinders were tested in compression according to ASTM C 39. The loading rate was 1.3 mm/min. Young's modulus and Poisson's ratio were determined from the stress-strain behaviour.

The bulk compressibility of the material was calculated using the following relationship:

$$C_{df} = \frac{3(1-2\nu)}{E} \quad (5.2)$$

A summary of the average values for elasticity and physical properties of the cement grout which can be used in the theoretical modelling is as follows:

Young's modulus,	E	=	19,231 MPa (± 124 MPa)
Poisson's ratio,	ν	=	0.21 (± 0.01)
Bulk compressibility,	C_{df}	=	90.479E-9 m ² /kN
Void ratio,	e	=	0.229 (± 0.006)
Porosity,	n	=	0.186

5.3 TEST SCHEDULE

Altogether, seven grout cylinders were used in preliminary tests to evaluate the effectiveness of the seals employed in the test apparatus. The three cylinders which were used in the final test program were previously untested and have been labelled as specimens 1, 2 and 3.

Three consecutive tests were carried out on each of the test specimens. The three tests are designated, in test sequence, as tests A, B and C. The tests were carried out in accordance with the test procedure described in section 3.8 using an initial pressure of 600 kPa. In all tests, water, at room temperature, was used as the permeating fluid. The properties of the water that were required for use in the theoretical calculations were taken from published values (see e.g. White, 1986). The parameters applicable to the general temperature and pressure ranges of the tests (room temperature; atmospheric pressure) are as follows:

Unit weight,	γ_w	=	9.81 kN/m ³
Viscosity,	μ	=	1.0E-6 kNs/m ²
Compressibility,	C_w	=	454.097E-9 m ² /kN

5.4 TEST RESULTS

The experimental data has been plotted in the form of dimensionless pressure ($P(t)/P_0$) versus time. The theoretical results for the pressure decay in the cylindrical cavity were generated using the model and the associated equations ((4.10) to (4.12)) presented in Chapter 4. The value of α for this series of tests was found to be less than

10 ($\alpha = 0.34$), therefore equation (4.12) was evaluated using the tables provided by Bredehoeft and Papadopoulos (1980).

The Figure 5.1 indicates the experimental results for the pressure decay in the cylindrical cavity (in broken lines) derived from the three tests conducted on the same sample of grout. The Figure 5.1 also contains the theoretical estimates for the pressure decay determined for several choices of K ranging from 10^{-17} m^2 to 10^{-23} m^2 . Analogous results obtained for the second and third specimens of the hardened cement grout are shown in Figure 5.2 and Figure 5.3 respectively. These graphical representations enable us to narrow down the range of interest in K which can be used to match closely the pressure-decay results derived from the three separate experiments. To achieve this, the range of values of K are selected within 10^{-19} m^2 and 10^{-21} m^2 . The Figures 5.4, 5.5 and 5.6 illustrate the more refined comparisons made between the experimentally derived pressure decay curves for sample 1 and the theoretically derived results. The same approach was adopted in making comparisons between theoretically derived results and the three experimental observations (A, B and C) obtained for tests conducted on the second (2) and third (3) grout cylinders. The sets of Figures 5.7 to 5.9 and 5.10 to 5.12 illustrate respectively the comparisons associated with the experimental data and the theoretical predictions.

Finally, the theoretical predictions which closely match the experimental observations yield the respective values of K . Admittedly, it is possible to strive for a perfect match between the experimental results and the theoretical predictions using statistical techniques (e.g. a least square fit). Such a fine degree of refinement is perhaps

unwarranted in view of the approximations invoked in the theoretical developments. For this reason, the correlation is established by interpolating the value of K for the experimental results from the values of K corresponding to the theoretical predictions which bound the experimental result. The average permeability of each specimen was calculated based on the results of the three tests (A, B and C). The results are shown in Table 5.1.

Sample	Test	Permeability (m ²)	Average Permeability (m ²)
1	A	18E-21	15.0E-21
	B	15E-21	
	C	12E-21	
2	A	6E-21	4.3E-21
	B	4E-21	
	C	2E-21	
3	A	9E-21	7.4E-21
	B	8E-21	
	C	6E-21	
Average	-	-	8.9E-21

Table 5.1 **Summary of results from permeability tests performed on three grout cylinders.**

5.5 OBSERVATIONS

The test program produced results of reasonable consistency and contributed to some interesting and potentially important observations. The major observations noted throughout the test program are summarized in the following items:

- a) Repeated tests on the same sample always produced permeability results within the same order of magnitude.
- b) For all three test samples, it was noted that the permeability decreased with each successive test. Although it cannot be confirmed, it could be argued that this may be due to continuing chemical reactions between the water and the cement grout. These reactions could be instrumental in the further hydration of the cement particles and/or mineral build-up which would lead to a reduction in the available pore space. This in turn can reduce the permeability of the grout.
- c) Hard, rough textured accretions were observed on the outside of the test specimens and on the wall of the stainless steel tank. Although the exact chemical composition of these deposits have not been determined, it is likely that they may occur as a by-product of the hydration process or as a result of geochemical reactions between the water and the grout.
- d) The theoretically determined pressure decay curves follow very closely those determined from the experiments. These appear to be decreasing with no observable abrupt changes in the slope of the pressure decay curve.
- e) The axial load which maintains the seal on the ends of the test cylinders shows virtually no change for the duration of the test. These results are shown in Figure 5.13

for short durations of the test, and in Figure 5.14 for longer durations. These observations are typical of all tests.

f) The temperature of the water bath remained constant throughout the duration of the test. Some fluctuations were observed in the results, but this is within the accuracy that was provided by the type K thermocouple. The temperatures recorded throughout test 1-A are shown in Figure 5.15 and Figure 5.16. These observations are typical of all tests.

Figure 5.1 Experimental pressure decay curves from three tests performed on test specimen 1 plotted along with theoretical decay curves corresponding to permeabilities from $1.0E-17 \text{ m}^2$ to $1.0E-23 \text{ m}^2$.

Figure 5.2 Experimental pressure decay curves from three tests performed on test specimen 2 plotted along with theoretical decay curves corresponding to permeabilities from $1.0E-17 \text{ m}^2$ to $1.0E-23 \text{ m}^2$.

Figure 5.3 Experimental pressure decay curves from three tests performed on test specimen 3 plotted along with theoretical decay curves corresponding to permeabilities from $1.0E-17 \text{ m}^2$ to $1.0E-23 \text{ m}^2$.

Figure 5.4

Test result from permeability test 1-A. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.5

Test result from permeability test 1-B. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.6

Test result from permeability test 1-C. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.7

Test result from permeability test 2-A. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.8 Test result from permeability test 2-B. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.9 Test result from permeability test 2-C. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.10 Test result from permeability test 3-A. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.11 Test result from permeability test 3-B. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.12 Test result from permeability test 3-C. The permeability corresponding to the experimental decay curve has been interpolated from the theoretical decay curves corresponding to known permeability values.

Figure 5.13 Typical response of the axial load during the time period in which experimental data was used for permeability determination. Results shown are for test 1-A.

Figure 5.14 Typical response of the axial load throughout the duration of a test. Results shown are for test 1-A.

Figure 5.15 Typical readings of the water bath temperature throughout the time period in which experimental data was used for permeability determination. Results shown are for test 1-A.

Figure 5.16 Typical readings of the water bath temperature throughout the test period. Results shown are for test 1-A.

6. CONCLUSIONS

The primary goal of this thesis was to develop a laboratory permeability test which can be used, relatively conveniently, to determine the permeability characteristics of rock, concrete and other low permeability cementitious materials. Such a test should be easy to perform, yield consistent results and use less complicated equipment and test procedures than those currently advocated in the literature. The development of the test focussed on a radial flow concept as opposed to rectilinear flow through cylindrical samples of the material.

The results derived from tests 1 through 3 are in the same range as results published by Bamforth (1987) and Banthia and Mindess (1989) for steady-state tests conducted on several different mixes of hardened cement pastes. The range of permeabilities found by these researchers was between $1\text{E-}21\text{ m}^2$ and $1000\text{E-}21\text{ m}^2$. The permeability of the grout measured using the test procedure described in this thesis ranged from $1\text{E-}21\text{ m}^2$ to $10\text{E-}21\text{ m}^2$. The results derived from repeated tests on the same sample were very similar. A slight decrease in permeability was observed for each successive test. This decrease is more likely to be as a consequence of precipitations resulting from chemical reactions between the permeating fluid and the grout, and not due to erratic test results. This conclusion is substantiated by the accumulation of a hard, rough textured residue on the outside face of the test cylinders and on the walls of the test chamber.

Contrary to the difficulties associated with its development, the test has evolved as one which can be performed relatively quickly, especially in comparison with many steady-state test procedures advocated in the literature. It was found that approximately

four days were required to saturate the samples. This time period could be reduced by using either smaller test samples or samples with a higher relative internal diameter. *The tests themselves were conducted for 3 hours, but only the data obtained for the first 10 minutes was required to determine the permeability of the material.* This estimate of time cannot be regarded as universally applicable, however. It is likely that data for longer periods of time would be required to accurately identify the permeability of materials with permeabilities lower than $1.0\text{E-}21 \text{ m}^2$. This is due to the fact that, for this range of permeabilities, the pressure decay in the central cavity is so small that the theoretical decay curves would be too closely spaced for accurate evaluation of the permeability. In the same token, the experimental procedure presented in this thesis would not be suitable for materials with permeabilities greater than $1.0\text{E-}17 \text{ m}^2$. In this range, the pressure in the central cavity will reduce very quickly and the decay curves corresponding to permeabilities of different orders of magnitude very quickly converge and become asymptotic to the time axis. It would therefore be difficult to obtain an accurate measure of the permeability using the exact test procedure, the test arrangement and the data acquisition mode described in the study. For materials with relatively high permeability it is necessary to adopt a data acquisition system where the scanning rate for the data can be substantially increased. In this case, the precise nonlinear nature of the pressure decay could be used to estimate the permeability.

The test equipment required to perform the proposed radial-flow transient pulse permeability test is much simpler than that for most other permeability tests. Due to the radially outward flow conditions, no confining pressure is required, therefore only one

fluid pressure supply is required. This is in direct contrast to most other tests which require two pressure supplies (one for the confining pressure and one for the permeating fluid). With a transient technique lower fluid pressures and smaller fluid volumes can be used. This factor combined with the radial flow geometry implies that the commonly used high-pressure cell can be replaced with a simple water container. These simplifications in test equipment lead to a much simpler test procedure and thus minimize the errors in the test results that are operator- dependent.

The accuracy of the results will depend on both the accuracy (or consistency) with which the experiments are carried out and also the accuracy of the material properties which are used in developing the theoretical decay curves. A complete analysis of the sensitivity of the theoretical solution to variations in the material parameters has not been carried out for this thesis, however, as an example, the variability in the porosity for the test results presented here would change the α parameter from 0.34 to 0.33. Searching the appropriate table (Appendix B), an insignificant difference in the value of $F(\alpha, \beta)$ would be obtained for any value of β . The results may be more sensitive to other parameters and further study is warranted.

The geometry of the proposed test apparatus provides radially outward flow conditions. This geometry is convenient for investigations into the flow of fluids through fractures and the effects of normal loads on this type of flow. The proposed apparatus should be adequate for performing tests for 'crack-permeability' research without any significant modifications. The only possible modifications required might be to the water pressure supply. The analysis of the test procedure would also be different.

References

Ahmed, U., Crary, S.F. and Coates, G.R., 1991, "Permeability Estimation: The Various Sources and Their Interrelationships", *Journal of Petroleum Technology*, Vol. 43, No. 5, pp. 578-587.

Bamforth, P.B., 1987, "The Relationship Between Permeability Coefficients for Concrete Obtained Using Liquid and Gas", *Magazine of Concrete Research*, Vol. 39, No.138, pp. 3-11.

Banthia, N. and Mindess, S., 1989, "Water Permeability of Cement Paste", *Cement and Concrete Research*, Vol. 19, pp. 727-736.

Bernaix, J., 1966, "New Laboratory Methods of Studying the Mechanical Properties of Rocks", *International Journal of Rock Mechanics and Mining Sciences*, Vol. 6, pp. 43-89.

Blair, S.C. and Berryman, J.G., 1991, "Estimates of Permeability and Relative Permeability for Sandstone Using Image Analysis of Cross Sections", *Rock Mechanics as a Multidisciplinary Science*, Roegiers (ed.), Balkema, Rotterdam, pp. 365-374.

Bourbie and Walls, 1982, "Pulse Decay Permeability: Analytical Solution and Experimental Test", *Society of Petroleum Engineers Journal*, Vol. 22, No. 5, pp. 719-721.

Brace, W.F., Walsh, J.B., and Frangos, W.T., 1968, "Permeability of Granite under High Pressure", *Journal of Geophysical Research*, Vol. 73, No. 6, pp. 2225-2236.

Bredehoeft, J.D. and Papadopoulos, I.S., 1980, "A Method for Determining the Hydraulic Properties of Tight Formations", *Water Resources Research*, Vol. 15, No. 1, pp. 233-238.

Cabrera, J.G. and Lynsdale, C.J., 1988, "A New Gas Permeameter for Measuring the Permeability of Mortar and Concrete", *Magazine of Concrete Research*, Vol. 40, No. 144, pp. 177-182.

Carslaw, H.S., and Jaeger, J.C., 1959, "*Conduction of Heat in Solids*", Oxford University Press.

Cooper, H.H., Bredehoeft, J.D. and Papadopoulos, I.S., 1967, "Response of a Finite-Diameter Well to an Instantaneous Charge of Water", *Water Resources Research*, Vol. 3, No. 1, pp. 263-269.

Daw, G.P., 1971, "A Modified Hoek-Franklin Triaxial Cell for Rock Permeability Measurements", *Geotechnique*, Vol. 21, No. 1, pp. 89-91.

Dewaele, P.J., Reardon, E.J. and Dayal, R., 1991, "Permeability and Porosity Changes Associated with Cement Grout Carbonation", *Cement and Concrete Research*, Vol. 21, pp. 441-454.

Dhir, R.K. and Byars, E.A., 1993, "PFA Concrete: Permeation Properties of Cover to Steel Reinforcement", *Cement and Concrete Research*, Vol. 23, pp. 554-566.

Dixon, R.S. and Rosinger, E.L.J., 1984, "*The Canadian Nuclear Fuel Waste Management Program: 1983 Annual Report*", AECL-7811.

Fetter, C.W., 1988, "*Applied Hydrogeology*", 2nd. ed., Merrill Publishing Company.

Fetter, C.W., 1993, *"Contaminant Hydrogeology"*, Macmillan Publishing Company.

Franklin, J.A. and Dusseault, M.B., 1989, *"Rock Engineering"*, McGraw-Hill Inc.

Freeman, D.L. and Bush, D.C., 1983, "Low-Permeability Laboratory Measurements by Nonsteady-State and Conventional Methods", *Society of Petroleum Engineers Journal*, Vol. 23, No. 6, pp. 928-936.

Goto, S. and Roy, D.M., 1981, "The Effect of W/C Ratio and Curing Temperature on the Permeability of Hardened Cement Paste", *Cement and Concrete Research*, Vol. 11, pp. 575-579.

Hearn, N. and Mills, R.H., 1991, "A Simple Permeameter for Water or Gas Flow", *Cement and Concrete Research*, Vol. 21, pp. 257-261.

Heystee, R. and Roegiers, J.C., 1980, "The Effect of Stress on the Primary Permeability of Rock Cores - A Facet of Hydraulic Fracturing", *Canadian Geotechnical Journal*, Vol. 18, pp. 195-204.

Hsieh, P.A., Tracy, J.V., Neuzil, C.E., Bredehoeft, J.D. and Silliman, S.E., 1980, "A Transient Laboratory Method for Determining the Hydraulic Properties of 'Tight' Rocks - Theory", *International Journal of Rock Mechanics, Mining Science and Geomechanics Abstracts*, Vol. 18, pp. 245-252.

Kay, T., 1992, *"Assessment & Renovation of Concrete Structures"*, Longman Scientific and Technical, John Wiley & Sons Ltd.

Knutson, C.F. and Bohor, B.F., 1963, "Reservoir Rock Behaviour Under Moderate Confining Pressure", *Fifth Symposium on Rock Mechanics*, University of Minnesota, MN., MacMillan, New York, NY, pp. 627-659.

Kosmatka, S.H., Panarese, W.C., Allen, G.E. and Cumming, S., 1991, "*CPCA: Design and Control of Concrete Mixtures*", Fifth Canadian Metric Edition, Portland Cement Association.

Kranz, R.L., Frankel, A.D., Engelder, T. and Scholz, C.H., 1979, "The Permeability of Whole and Jointed Barre Granite", *International Journal of Rock Mechanics, Mining Sciences and Geomechanics Abstracts*, Vol. 16 pp. 225-234.

Lin, W., 1982, "Parametric Analyses of the Transient Method of Measuring Permeability", *Journal of Geophysical Research*, Vol. 87, No. B2, pp. 1055-1060.

Lyon, R.B., 1980, "*Environmental Assessment for Nuclear Fuel Waste Disposal - The Canadian Program*", AECL TR-91.

Martin, G.R., 1986, "A Method for Determining the Relative Permeability of Concrete Using Gas", *Magazine of Concrete Research*, Vol. 38, No. 135, pp. 90-94.

Neuzil, C.E., Cooley, C., Silliman, S.E., Bredehoeft, J.D. and Hsieh, P.A., 1981, "A Transient Laboratory Method for Determining the Hydraulic Properties of 'Tight' Rocks - II Application", *International Journal of Rock Mechanics, Mining Science and Geomechanics Abstracts*, Vol. 18, pp. 253-258.

Olsen, H.W., Nichols, R.W. and Rice, T.L., 1985, "Low Gradient Permeability Measurements in a Triaxial System", *Geotechnique*, Vol. 35, No. 2, pp. 145-157.

Poon, C.S., Clark, A.I., Perry, R., Barker, A.P. and Barnes, P., 1986, "Permeability Study on the Cement Based Solidification Process for the Disposal of Hazardous Wastes", *Cement and Concrete Research*, Vol. 16, pp. 161-172.

Papadopoulos, I.S., Bredehoeft, J.D. and Cooper, H.H., 1973, "On the Analysis of 'Slug Test' Data", *Water Resources Research*, Vol. 9, No. 4, pp. 1087-1089.

Powers, T.C., Copeland, L.E., Hayes, J.C. and Mann, H.M., 1954, "Permeability of Portland Cement Paste", *American Concrete Institute*, Vol. 51, No.14, pp. 285-298.

Rehbinder, G. 1978, "Measurement of the Average Pore Velocity of Water Flowing Through a Rock Specimen", *Rock Mechanics*, Vol. 11, pp. 19-28.

Sanyal, S.K., Pirnie III, R.M., Chen, G.O. and Marsden, S.S. Jr., 1972, "A novel Liquid Permeameter for Measuring Very Low Permeability", *Society of Petroleum Engineers Journal*, Vol. 12, No. 3, pp. 206-210.

Schlueter, E.M., Cook, N.G.W., Zimmerman, R.W. and Witherspoon, P.A., 1991, "Predicting Permeability and Electrical Conductivity of Sedimentary Rocks from Microgeometry", *Rock Mechanics as a Multidisciplinary Science*, Roegiers (ed.), Balkema, Rotterdam, pp. 355-364.

Seely, F.B. and Smith, J.O., 1967, "*Advanced Mechanics of Materials*", Second Edition, John Wiley & Sons Ltd.

Selvadurai, A.P.S., 1994, *A Theoretical Analysis of the Pulse Test for a Finite Cylinder*, unpublished work.

Trimmer, D.A., 1981, "Design Criteria for Laboratory Measurements of Low Permeability Rocks", *Geophysical Research Letters*, Vol. 8, No. 3, pp. 973-975.

van der Muelen, A.S. and van Dijk, J., 1969, "A Permeability-Testing Apparatus for Concrete", *Magazine of Concrete Research*, Vol. 21, No. 67, pp. 121-123.

White, F.M., 1986, "*Fluid Mechanics*", 2nd. ed., McGraw-Hill Inc.

Wright, E.D. (compiler), 1991, "*Semi-annual Report of the Canadian Nuclear Fuel Waste Management Program: 1990 October 1 - 1991 March 31*", AECL TR-425-10.

Appendix A

From the theory of thick-walled cylinders (Seely and Smith, 1967), the maximum tensile stress in the cylinder under conditions of internal pressure is given by:

$$\sigma_{Tmax} = P \frac{r_2^2 + r_1^2}{r_2^2 - r_1^2}$$

where: P = internal pressure (kPa)
 r_1 = inside diameter (m)
 r_2 = outside diameter (m)

For the test specimens used in this research: $r_1 = 0.0127$ m

$r_2 = 0.0762$ m

The compressive strength of the grout material was 60 MPa. If we assume that the tensile strength is 10 % of the compressive strength and then incorporate a safety factor of 3, we get an allowable tensile stress of 2 MPa (2000 kPa). Using the above equation and the dimensions of the test specimen, the maximum allowable pressure in the central cavity is 1,892 kPa (274 psi.).

Using a test pressure of 600 kPa therefore provides a factor of safety against tensile failure of the test specimen of greater than 9.

Appendix B

Tt/τ_c^2	H/H_0				
	$\alpha = 10^{-1}$	$\alpha = 10^{-2}$	$\alpha = 10^{-3}$	$\alpha = 10^{-4}$	$\alpha = 10^{-5}$
1.00×10^{-1}	0.9771	0.9920	0.9969	0.9985	0.9992
2.15×10^{-2}	0.9655	0.9876	0.9949	0.9974	0.9985
4.64×10^{-3}	0.9490	0.9807	0.9914	0.9954	0.9970
1.00×10^{-2}	0.9235	0.9693	0.9853	0.9915	0.9942
2.15×10^{-3}	0.8860	0.9505	0.9744	0.9841	0.9889
4.64×10^{-4}	0.8293	0.9187	0.9545	0.9701	0.9781
1.00×10^{-3}	0.7460	0.8655	0.9183	0.9434	0.9572
2.15×10^{-4}	0.6259	0.7782	0.8538	0.8935	0.9167
4.64×10^{-5}	0.4782	0.6436	0.7436	0.8031	0.8410
1.00×10^{-4}	0.3117	0.4598	0.5729	0.6520	0.7050
2.15×10^{-5}	0.1665	0.2597	0.3543	0.4364	0.5038
4.64×10^{-6}	0.07415	0.1086	0.1554	0.2082	0.2620
1.00×10^{-5}	0.04625	0.06204	0.08519	0.1161	0.1521
2.15×10^{-6}	0.03065	0.03780	0.04821	0.06355	0.08378
4.64×10^{-7}	0.02092	0.02414	0.02844	0.03492	0.04426
1.00×10^{-6}	0.01297	0.01414	0.01545	0.01723	0.01999
2.15×10^{-7}	0.009070	0.009615	0.01016	0.01083	0.01169
4.64×10^{-8}	0.005711	0.005919	0.006111	0.006319	0.006554
1.00×10^{-7}	0.003722	0.003809	0.003884	0.003962	0.004046
2.15×10^{-8}	0.002377	0.002418	0.002453	0.002488	0.002525
4.64×10^{-9}	0.001179	0.001187	0.001194	0.001201	0.001208

Table of $F(\alpha, \beta)$ values for 5 orders of magnitude of α , from $\alpha = 10^{-1}$ to 10^{-5} .
 Note that $Tt/\tau_c^2 = \beta$. (after Cooper et. al., 1967)

Tt/r_c^2	$\alpha = 10^{-6}$	$\alpha = 10^{-7}$	$\alpha = 10^{-8}$	$\alpha = 10^{-9}$	$\alpha = 10^{-10}$
0.001	0.9994	0.9996	0.9996	0.9997	0.9997
0.002	0.9989	0.9992	0.9993	0.9994	0.9995
0.004	0.9980	0.9985	0.9987	0.9989	0.9991
0.006	0.9972	0.9978	0.9982	0.9984	0.9986
0.008	0.9964	0.9971	0.9976	0.9980	0.9982
0.01	0.9956	0.9965	0.9971	0.9975	0.9978
0.02	0.9919	0.9934	0.9944	0.9952	0.9958
0.04	0.9848	0.9875	0.9894	0.9908	0.9919
0.06	0.9782	0.9819	0.9846	0.9866	0.9881
0.08	0.9718	0.9765	0.9799	0.9824	0.9844
0.1	0.9655	0.9712	0.9753	0.9784	0.9807
0.2	0.9361	0.9459	0.9532	0.9587	0.9631
0.4	0.8829	0.8995	0.9122	0.9220	0.9295
0.6	0.8345	0.8569	0.8741	0.8875	0.8984
0.8	0.7901	0.8173	0.8383	0.8550	0.8686
1.0	0.7489	0.7801	0.8045	0.8240	0.8401
2.0	0.5800	0.6235	0.6591	0.6889	0.7139
3.0	0.4554	0.5033	0.5442	0.5792	0.6096
4.0	0.3613	0.4093	0.4517	0.4891	0.5222
5.0	0.2893	0.3351	0.3768	0.4146	0.4487
6.0	0.2337	0.2759	0.3157	0.3525	0.3865
7.0	0.1903	0.2285	0.2655	0.3007	0.3337
8.0	0.1562	0.1903	0.2243	0.2573	0.2888
9.0	0.1292	0.1594	0.1902	0.2208	0.2505
10.0	0.1078	0.1343	0.1620	0.1900	0.2178
20.0	0.02720	0.03343	0.04129	0.05071	0.06149
30.0	0.01256	0.01445	0.01667	0.01936	0.02320
40.0	0.008337	0.008896	0.009637	0.01062	0.01190
50.0	0.006209	0.006470	0.006789	0.007192	0.007709
60.0	0.004961	0.005111	0.005283	0.005487	0.005735
80.0	0.003547	0.003617	0.003691	0.003773	0.003863
100.0	0.002763	0.002803	0.002845	0.002890	0.002938
200.0	0.001313	0.001322	0.001330	0.001339	0.001348

Table of $F(\alpha, \beta)$ values for 5 orders of magnitude of α , from $\alpha = 10^{-6}$ to 10^{-10} .
Note that $Tt/r_c^2 = \beta$. (after Papadopoulos et. al., 1973)

β	$\alpha=0.1$	$\alpha=0.2$	$\alpha=0.5$	$\alpha=1$	$\alpha=2$	$\alpha=5$	$\alpha=10$
0.000001	0.99993	0.99990	0.99984	0.99977	0.99968	0.99948	0.99923
0.000002	0.99990	0.99984	0.99977	0.99968	0.99955	0.99927	0.99894
0.000004	0.99984	0.99975	0.99968	0.99955	0.99936	0.99898	0.99853
0.000006	0.99982	0.99971	0.99961	0.99945	0.99922	0.99876	0.99822
0.000008	0.99980	0.99965	0.99955	0.99936	0.99910	0.99857	0.99796
0.00001	0.99977	0.99965	0.99945	0.99929	0.99900	0.99841	0.99773
0.00002	0.99968	0.99955	0.99925	0.99900	0.99858	0.99776	0.99683
0.00004	0.99955	0.99934	0.99894	0.99858	0.99801	0.99687	0.99558
0.00006	0.99944	0.99922	0.99877	0.99827	0.99757	0.99619	0.99464
0.00008	0.99936	0.99909	0.99858	0.99800	0.99720	0.99562	0.99387
0.0001	0.99928	0.99894	0.99841	0.99777	0.99688	0.99512	0.99316
0.0002	0.99894	0.99857	0.99774	0.99687	0.99582	0.99321	0.99059
0.0004	0.99855	0.99797	0.99685	0.99560	0.99409	0.99061	0.89711
0.0006	0.99822	0.99752	0.99615	0.99465	0.99258	0.98869	0.88458
0.0008	0.99774	0.99713	0.99547	0.99385	0.99151	0.98711	0.88253
0.001	0.99759	0.99675	0.99505	0.99315	0.99057	0.88576	0.88079
0.002	0.99470	0.99446	0.99307	0.99048	0.98702	0.88075	0.87450
0.004	0.99528	0.99357	0.99031	0.98686	0.98232	0.87439	0.86684
0.006	0.99417	0.99211	0.98825	0.98419	0.97896	0.87001	0.86178
0.008	0.99322	0.99069	0.98654	0.98202	0.97626	0.86662	0.85797
0.01	0.99238	0.98982	0.98504	0.98017	0.97400	0.86384	0.85492
0.02	0.99004	0.98562	0.97947	0.97336	0.96595	0.85450	0.84517
0.04	0.98421	0.97980	0.97214	0.96489	0.95454	0.84454	0.83556
0.06	0.98048	0.97544	0.96697	0.95919	0.95055	0.83872	0.83030
0.08	0.97734	0.97190	0.96286	0.95486	0.94618	0.83469	0.82682
0.1	0.97459	0.96865	0.95951	0.95137	0.94276	0.83168	0.82428
0.2	0.96418	0.95774	0.94799	0.94010	0.93234	0.82313	0.81740
0.4	0.95095	0.94458	0.93566	0.92902	0.92292	0.81612	0.81207
0.6	0.94227	0.93642	0.92864	0.92311	0.91817	0.81280	0.809616
0.8	0.93598	0.93172	0.92397	0.91931	0.91521	0.81077	0.808134
1.	0.93117	0.92448	0.92061	0.91653	0.91315	0.809375	0.807120
2.	0.91744	0.91519	0.91202	0.90912	0.90604	0.805940	0.804620
4.	0.90761	0.90638	0.90420	0.90521	0.90468	0.803621	0.802908
6.	0.905527	0.90499	0.90431	0.903830	0.90324	0.802663	0.802185
8.	0.903943	0.903652	0.903254	0.902933	0.902554	0.802125	0.801771
10.	0.903065	0.902570	0.902670	0.902374	0.902130	0.801774	0.801499
20.	0.901476	0.901361	0.901248	0.901219	0.901133	0.8009943	0.8008716
40.	0.9014490	0.9014568	0.9014774	0.9016171	0.9015997	0.8005395	0.8004898
60.	0.9014767	0.9014318	0.9014229	0.9014132	0.9013964	0.8003726	0.8003445
80.	0.9013742	0.9013214	0.9013163	0.9013105	0.9013022	0.8002853	0.8002668
100.	0.9012577	0.9012559	0.9012526	0.9012487	0.9012471	0.8002313	0.8002181
200.	0.9011271	0.9011264	0.9011258	0.9011247	0.9011230	0.8001194	0.8001149
400.	0.9006707	0.9006295	0.9006272	0.9006242	0.9006195	0.8000605	0.80005944
600.	0.9004193	0.9004189	0.9004177	0.9004163	0.9004141	0.8000407	0.80004016
800.	0.9003140	0.9003137	0.9003131	0.9003123	0.9003110	0.80003078	0.80003035
1000.	0.9002510	0.9002508	0.9002504	0.9002496	0.9002490	0.80002469	0.80002440

Table of $F(\alpha, \beta)$ values for values of $\alpha = 0.1, 0.2, 0.5, 1, 2, 5$ and 10 .
(after Bredehoeft and Papadopoulos, 1980)

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