PERMEABILITY AND DURABILITY OF HIGH VOLUME FLY ASH CONCRETE UNDER AN APPLIED COMPRESSIVE STRESS

by

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

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(CIVIL ENGINEERING)

THE UNIVERSITY OF BRITISH COLUMBIA

September 2005

ABSTRACT

The durability of concrete is one of its most important properties and has been an attractive subject for research in recent years. One of the criteria, which determine concrete durability, is permeability. Transport processes in concrete have been investigated for several decades. However, the correlation between transport coefficients and applied stress has received only little attention. The scope of this study encompassed two major research focuses. The first involved developing a test method capable of measuring the water permeability of concrete under an applied stress. The second involves investigating the permeability of high volume fly ash (HVFA) concrete at early ages.

Two sets of tests were carried out. Special emphasis was placed on understanding the influence of stress application on the permeability of concrete at early ages (1-3 days). In the first set, four normal concrete mixes were investigated for effects of stress on early age concrete. In the second set, three high volume fly ash (HVFA) mixes were made to investigate the effects of fly ash on the permeability of fresh concrete. For each mixture, three 100 x 200 mm cylinders and 2 cylindrical hollow core specimens with a 50 mm diameter hollow cylindrical core at the center were cast. The cylindrical specimens were used to determine the compressive strength. The hollow core specimens were placed in specially designed cells such that water would permeate under pressure, and the collected water was drained out to a collection reservoir where its mass was measured by a computer-controlled scale.

In the first set, one of the permeability cells was mounted in a testing machine to apply a certain compressive stress on the specimen during the test, but in the second set, permeability of normal concrete were compared with HVFA concrete without stress. Results indicated that the presence of a compressive stress below a certain threshold value decreased the permeability, but when the applied stress exceeded this threshold, a significant increase in the permeability occurred. Addition of fly ash as a supplementary cementing material due to the retardation and slow strength gain in concrete, increases the permeability of fly ash concrete at early ages.

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ACKNOWLEDGEMENT

I thank GOD for guiding me through this Master process. I would like to express my sincere appreciation and profound gratitude to my supervisor Professor Nemkumar Banthia for all of his continuous guidance and support over the past 2 years. I also thank him for giving me an opportunity to work with a strong and friendly group. He was not just a supervisor for me in this period; he is my best model for my entire life. My acknowledgments also go to my co-supervisor Dr. L Li for her advice, support and guidance throughout this research.

I hereby acknowledge and thank to my advisors Prof. S. Mindess and Dr. Patrick F.McGrath for their helpful suggestions during the various stages of preparing this thesis. My acknowledgments also go to my colleagues, Reza Soleimani, Fariborz Majdzadeh, Rishi Gupha, Vivek Bindiganavile, Reza Mortazavi, Tiffany lin, Yashar Khalighi, Hanfeng Xu, Rose Mary Chacko, Zhange LiHe and David Woo for their friendly environment and helpful advise.

Thanks also go to Mr. Harald Schrempp, Mr. Doug Smith Mr. and John Wong for their technical support and advice in this research. I would like to thank the Cement Association of Canada for financial support.

I am grateful to my parents, Naser and Mohtaram, my wife, Nahid, and my son, Milad, for being with me and supporting me with their love. Finally, I would like to thank everyone who was involved in helping me to successfully complete this research project includes people and friends not mentioned above.

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 CONCRETE DURABILITY

Concrete has been widely used as a major construction material. Its low cost, versatility, adequate engineering properties and the easy availability of the constituent materials makes its utilization more attractive than other construction materials. Research efforts have been diverted towards producing a stronger concrete. This was done mainly by developing a better understanding of concrete technology. As a result, it is now possible to produce ultra high strength concrete exceeding strengths of 200 MPa. In the efforts of improving the strength of concrete the implications of these developments on its durability were not envisioned [1].

It has been recognized that in most instances deterioration in concrete is due to lack of adequate durability, rather than deficient strength [2]. Concrete structures have increasingly become unserviceable due to gradual deterioration arising from concrete deterioration and steel corrosion.

Hence, due to its economic and technical importance, reducing concrete deterioration and increasing its durability are becoming challenging problems facing the industry. The economic loss due to deterioration of concrete and steel corrosion may constitute up to several percentage points of a countries gross national product [3].

Concrete deterioration can be due to adverse physical, or chemical condition. Often one or more deterioration mechanisms are at work by the time a problem is identified. In fact, in terms of deterioration of concrete due to physical or chemical causes, the mobility of fluids or gases through the concrete are nearly always involved. The overall susceptibility, or penetrability of a concrete structure, especially when compounded by additional environmental or exposure challenges, is the key to its ultimate serviceability and durability. The common feature of these attacks is that all of them can result in cracking and spalling of the concrete surface [4].

Durability of concrete can be defined as its ability to resist weathering action, chemical attack, abrasion, or any other processes of deterioration and thereby retain its original shape, dimensions, quality and serviceability [5]. No material by itself is universally durable or not durable; it is in the context of its interaction with the in-service environment that determines its durability. Durable concrete is concrete that will withstand the conditions for which it has been designed, without deterioration, over a period of its expected service life. Durability is not an attribute of concrete in itself, but is rather a conclusion reached in the case of a specific concrete subject to specific service environment. A concrete is ''durable'' if, in its environment, it has provided the desired service life, without excessive cost for maintenance and repair due to degradation or deterioration.

A concrete mixture design is only an intended proportion of ingredients. If the concrete mixture is not transported, placed or cured properly it will not exhibit the desired performance qualities (Figure 1.1). Not only does the durability depend on proper formation of cement past, but it also depends on connectivity of the pores and integrity of the cement paste. The connectivity of the pores controls the ease with which agents can transport themselves through concrete. The integrity of the porous solid network controls the mechanical properties.

When concrete is properly designed and carefully produced with good quality control, it is an inherently durable material. Five factors that may affect the durability of concrete are constituent materials, construction practices, physical properties, environmental exposure conditions, and the type of loads. Once the concrete is in-place, prolonged exposure to adverse conditions may lead to deleterious attacks including corrosion of reinforcing steel, freezing and thawing action, sulfate attack, alkali-silica and alkali-carbonate reaction [6].

One of the parameters, which has the largest influence on durability, is the water to cement ratio. Water to cement ratio dictates the porosity and permeability of the paste. A higher water to cement ratio decreases the strength of concrete and its resistance to internal and external stresses.

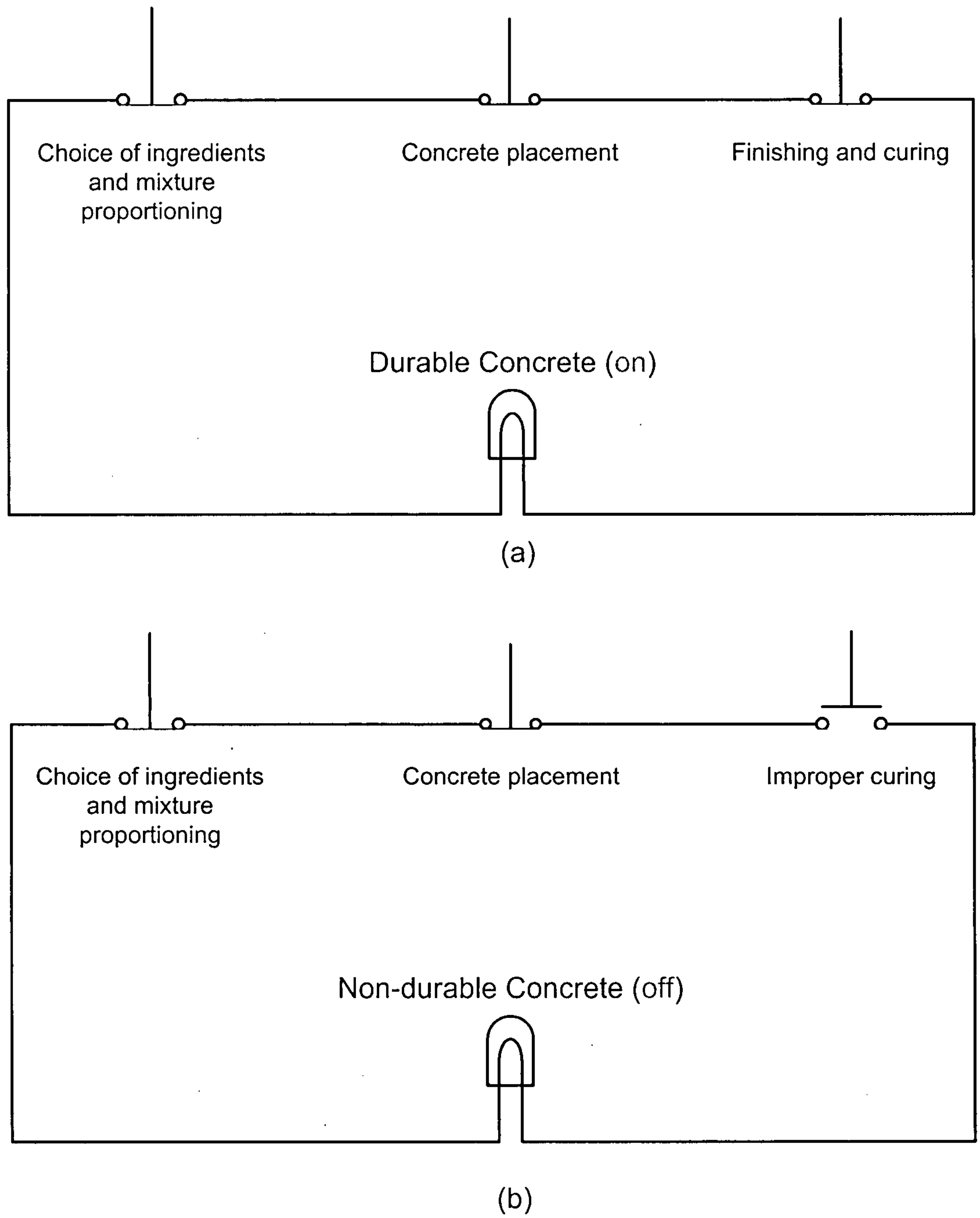


Figure 1.1. **Concrete Durability (a) Proper conditions make a durable system (b) Lack of materials, mix or even one improper condition may cause concrete to be non-durable**

1.1.1 PERMEABILITY - DURABILITY RELATIONSHIP

It is well known that permeability determines the vulnerability of concrete to external agencies, and in order to be durable, concrete must be relatively impervious. Concrete durability depends largely on the ease or difficulty with which gases or fluids can migrate through the hardened concrete mass. As the permeation of concrete decreases, its durability performance, in terms of physicochemical degradation, increases. Permeation controls the ingress of moisture, ionic and gaseous species into concrete [7]. Given that most deleterious agents are transported through water and water itself is one of the deleterious agents, the durability of any concrete depends largely on the permeability of concrete. The rate of deterioration may be accelerated by poor quality concrete, which is influenced by the inadequate selection of materials and/or poor concrete construction practices [8].

1.2 CONCRETE PERMEABILITY

1.2.1 INTRODUCTION

Permeability is defined as the movement of fluid through a porous medium under an applied pressure head, and is the most important property of concrete governing its long-term durability. Permeability of concrete, in turn, is influenced by three primary factors: porosity and interconnectivity of pores in the cement paste, and micro-cracks in the concrete, especially at the paste-aggregate interface.

Porosity and interconnectivity are controlled for most part by the water/cement (w/c) ratio, degree of hydration, and the degree of compaction. Density and location of interfacial micro-cracks, on the other hand, are determined by the level of applied stress, external or internal, experienced by the concrete.

1.2.2 PERMEATION

Concrete is a heterogeneous composite of coarse and fine aggregate particles held together by cement paste. Cement paste is a porous material and is sensitive to water movement surrounding the material and the flow of water into and out of the material. The pore structure is formed during the hydration process.

Winslow's [9] showed that, at similar low degrees of hydration, the paste in concrete has developed similar pore structure with the paste hydrating in the absence of aggregate. The difference becomes prominent as the degree of hydration increases. In general, permeability of concrete is a function of the w/c ratio, aggregate particle size, and pore size and distribution.

There are a variety of pores and voids in concrete, which can have direct effects on the permeability of concrete. Pores and voids in concrete can be broadly classified as gel pores and capillary pores.

In addition, there are pores in paste-aggregate interracial zones and porosity in the aggregate itself.

1.2.2.1 GEL POROSITY

Gel pores are the smallest interconnected interstitial spaces, which are formed during hydration. [37]. The average diameter of a stable gel pore is assumed to be about 2nm. Gel pores contribute to the possibilities of fluid transport across cement paste but in a very limited way. According to Powers [29] the water permeability of this phase is only $7x\ 10^{-16}$ m/s. Hence, gel pores cannot play a big role in the permeability of concrete [10].

1.2.2.2 CAPILLARY POROSITY

Capillary pores represents that part of the gross volume of concrete that is not filled by the products of hydration. These pores start to fill up with hydration products and their volume is reduced with the progress of hydration. For a paste the w/c ratio and the degree of hydration determine the total capillary porosity.

Generally the capillary porosity increases as the w/c ratio increases. At a w/c ratio approximately 0.6, the capillary voids become connected, causing a rapid increase in the coefficient of permeability [11].

At the start of hydration, there is a slight decrease in capillary porosity together with a significant segmentation of the large pores [10], thus considerably reducing the possibilities of fluid transfer across the cement paste. Metha [11] indicates that above a threshold of 30% capillary porosity, the pores are so tortuously interconnected that a slight change in paste porosity does not result in a significant change in the permeability. Under theses conditions, permeability is around 10^{-14} m/s.

1.2.2.3 PASTE-AGGREGATE INTERFACIAL ZONE POROSITY

Theoretically concrete can be assumed as a two-phase material (Fig. 1.2), aggregate and cement paste.

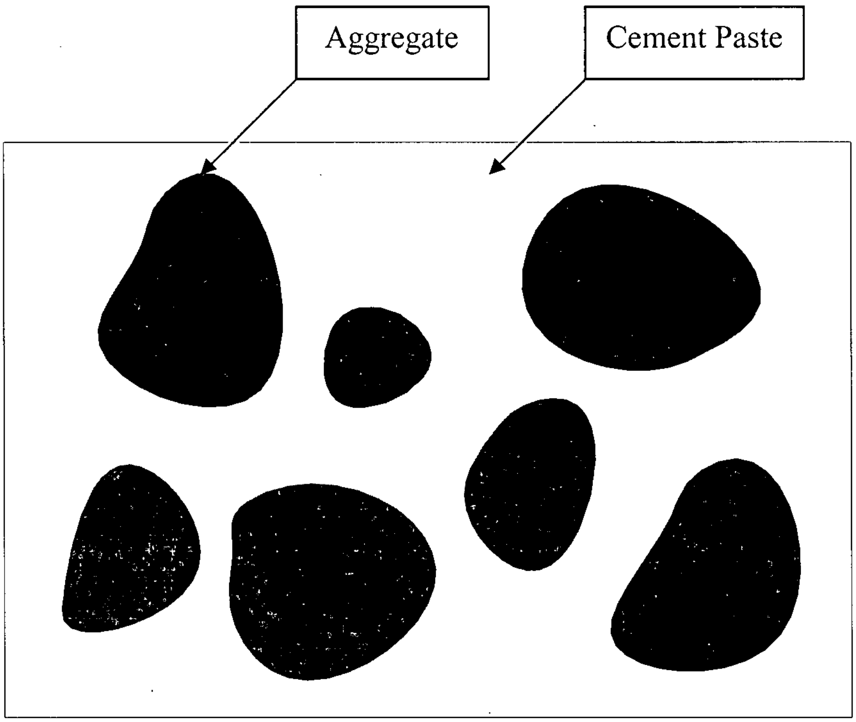


Figure 1.2. **Two phase theory**

In consequence, adding low-permeable aggregates to cement paste should reduce concrete permeability by interrupting capillary pore continuity in the cement paste matrix. However, test results indicate that the opposite is true [10]. Data in Figure 1.3

shows the considerable increases in permeability when aggregate are added to a paste or mortar.

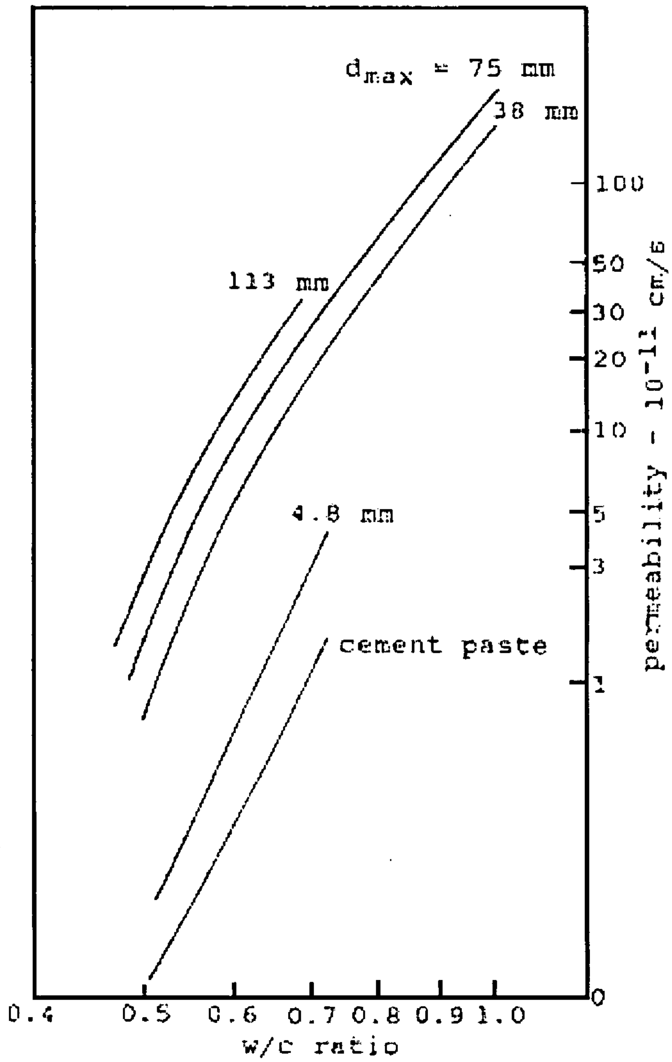


Figure 1.3. **Influence of w/c ratio and maximum aggregate size upon the water permeability of concrete [10].**

In fact, concrete is a three-phase material: aggregate, cement paste and interfacial transition zone (ITZ) (Figure 1.4).

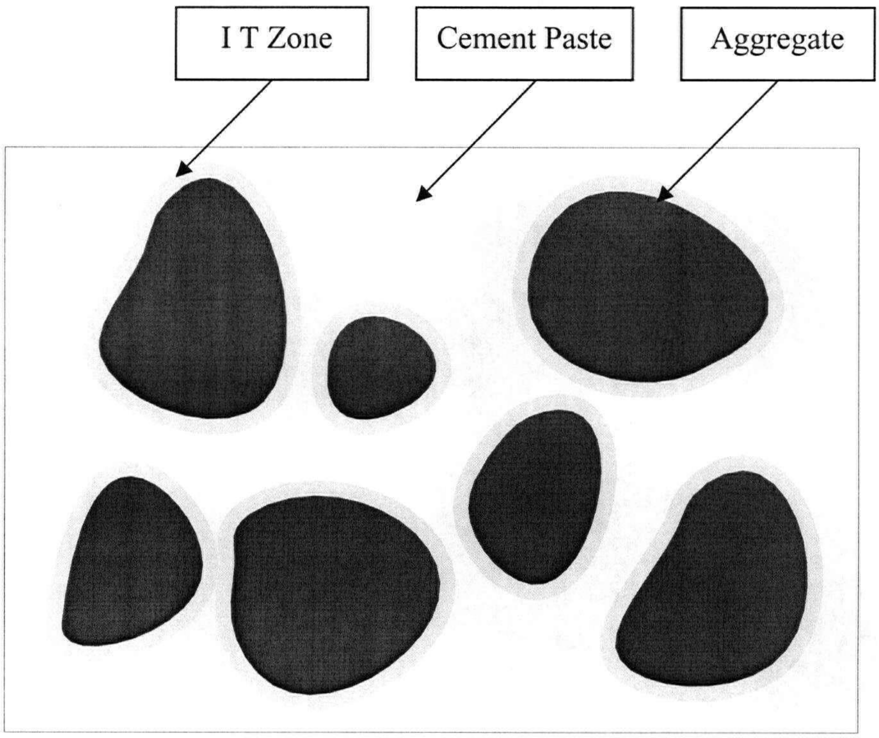


Figure 1.4. **Three phase theory**

The porosity of the paste - aggregate interfacial zone is usually much higher than the rest of the paste matrix. The different pore structure of ITZ around aggregate is due to bleeding, the higher local w/c ratio, preferential growth of Ca $(OH)_2$ crystals and the influence of aggregate surface [12].

The ITZ is normally of the order of 50 nm in thickness, and can occupy 30 - 50% of the total volume of cement paste in concrete [13]. In comparison to the bulk hydrated cement paste, the paste-aggregate interfacial zone is weaker, carries leach able compounds, and can be the least resistant path for migrating moisture and other harmful substances.

1.2.2.4 AGGREGATE POROSITY

The term aggregate porosity refers to the volume inside the individual aggregate particles that is not occupied by solids [38]. The values of coefficient of permeability, presented by Powers [39], vary from 3.45×10^{-13} cm/s for a dense trap rock to 2.18×10^{-9} cm/s for a porous granite. A distinction is frequently made between the total porosity and the part that is interconnected and called the effective porosity.

The "effective" pore space permits the penetration and retention of water or other liquids into the aggregate. Many properties of the concrete are significantly or even critically affected by aggregate porosity. The particle size of the aggregate also plays an important role in the permeability of concrete, the larger the aggregate size, the greater the coefficient of permeability [8].

1.2.2.5 MICRO CRACKS

In addition to the large volume of capillary voids and oriented calcium hydroxide crystals, a major factor responsible for the poor strength and high permeability of the transition zone in concrete is the presence of micro cracks. The amount of micro cracks depends on numerous parameters, including aggregate size and grading, cement content, w/c ratio, degree of consolidation of fresh concrete, curing conditions, environmental humidity, and thermal history of concrete [11].

Concrete has micro cracks in the transition zone even before a structure is loaded [11]. Clearly, short-term impact loads, drying shrinkage, and sustained loads at high levels will increase the size and number of micro cracks. During the initial stages of hydration the transition zone is weak and cracking may occur due to differential strains between the cement paste and the aggregate, which are caused by drying shrinking, thermal strains, and externally applied loads. The micro-cracks that occur in the transition zone are larger in width than most capillary cavities present in the cement paste matrix.

Interfacial micro-cracks help to establish interconnectivity in the pore structure, which leads to increased permeability of the system. Such a chain reaction of "deterioration →cracking →more permeable concrete →further deterioration" may eventually result in destructive deterioration of the concrete structure [14]. Therefore, it is significant to understand the mutual interaction and relationship between concrete cracks and its permeability (Figure 1.5).

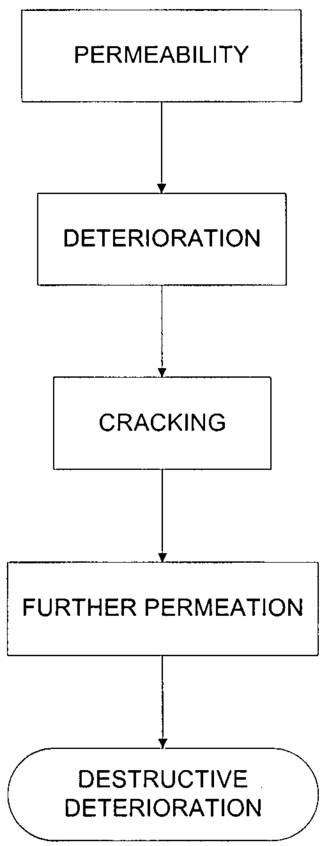
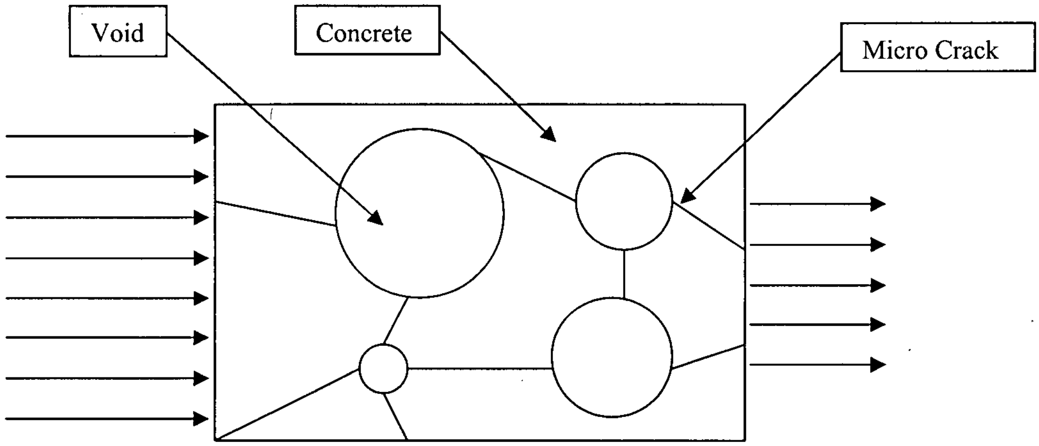


Figure 1.5. **Permeability Chain Diagram**

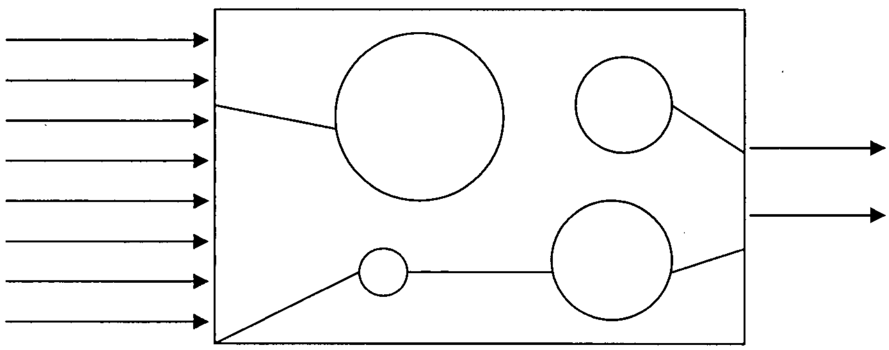
1.2.3 POROSITY AND PERMABILTY

In any composite material, the properties of the constituents and the interactions between them determine the behavior of the material. Concrete is a composite material with coarse and fine aggregates embedded in a cement paste matrix. As such, the aggregate, the cement paste and the interfacial zone between them influence the permeability of concrete. In concrete, it is generally not the porosity but the pore structure that is essential in establishing the permeability [15].

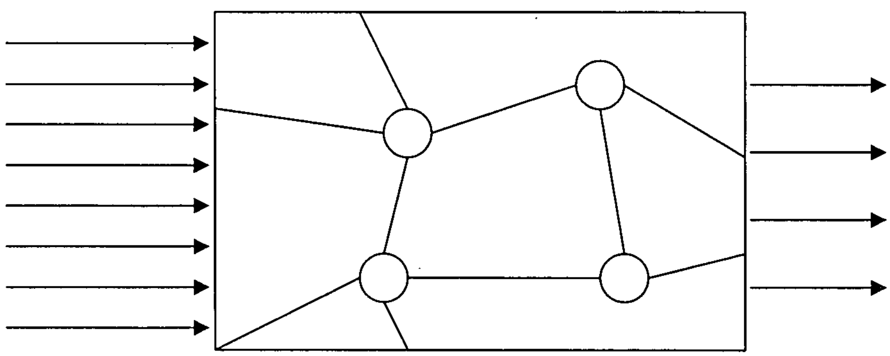
Further, micro cracks in the matrix contribute significantly to the permeability. The permeability of concrete is determined by both the total porosity and its distribution [16]. Figure 1.6 shows the difference between porosity and permeability schematically, and it indicates that the connectivity of the pore system is a prerequisite for permeability and interconnected pores are mainly responsible for the permeability of concrete. A material can be porous and still be impermeable as long as the pores are not interconnected.



High Porosity, High Permeability



High Porosity, Low Permeability



Low Porosity, High Permeability

Figure 1.6. **Permeability, Porosity, and Micro crack Relationship**

1.2.4 WATER PERMEABILITY

Water is the most significant fluid that flows through concrete. In porous materials water permeability usually determines the rate of deterioration. Water can be directly involved in physical processes leading to degradation, especially during the repeated freezing and thawing cycles. In addition water also serves as the carrying agent for soluble aggressive ions that can be the source of chemical degradation. Darcy's Law under slow, unidirectional, steady flow governs water permeability [8] is given by:

$$K_w = \frac{QL}{A\Delta h} \qquad \text{Equation (1.1)}$$

where

K_w = Coefficient of water permeability (m/s)

Q = Rate of Water Flow (m^3/s)

L = Thickness of specimen wall or flow path length (m)

A = Permeation area (m^2)

Δh = Pressure head (m)

Water permeability of concrete with different crack widths was evaluated, and the results indicated that concrete permeability increased with crack width [14]. The degree of the permeability increase depends on the extent of crack opening in the concrete. When a crack opening displacement (COD) was small, less than 50 microns under loading, the crack opening had little effect on concrete permeability. With the crack opening displacement increasing, from 50 to 200 microns, concrete permeability increased rapidly. When the crack opening displacement was large, beyond 200 microns [14], the rate of increase of water permeability becomes steady and less rapid (Figure 1.7).

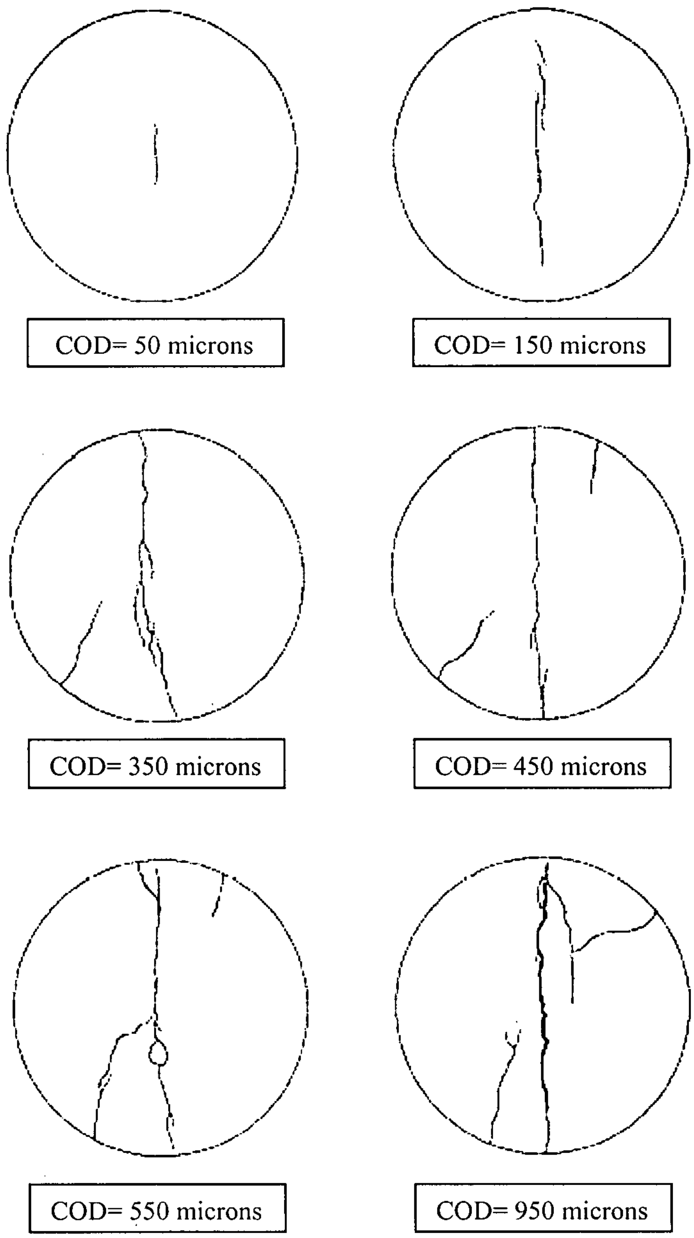


Figure 1.7. **Crack Patterns for Different COD [14]**

One model [17] used to analyze the initial flow of water through cracks in concrete was derived from the parallel-plate theory and is described in fluid mechanics textbooks. This model assumes the fluid flow to be incompressible and the flow to be laminar between parallel sides of plates in the material [17]. The equation, which is derived from this model to estimate the water flow through a smooth parallel-side crack, can be written as

$$q_o = \xi \, . \, \Delta p \, . \, b \, . \, w^3 / 12. \, \eta \, . \, d \qquad \text{Equation (1.2)}$$

where

q_o = water flow (m^3/sec)

ξ = reduction factor comprising the roughness of cracks

Δp = differential water pressure (N/m^2)

b = length of crack (m)

w = crack width (m)

η = absolute viscosity

d = thickness of the concrete (m)

Equation (1.2), often referred to as Poiseuille Law, shows that the crack width is the dominant factor for the water permeability as the flow rate is proportional to the width cubed. Figure 1.8 shows a general overview of the main parameters involved in concrete permeability. These parameters will be discussed in the following chapters.

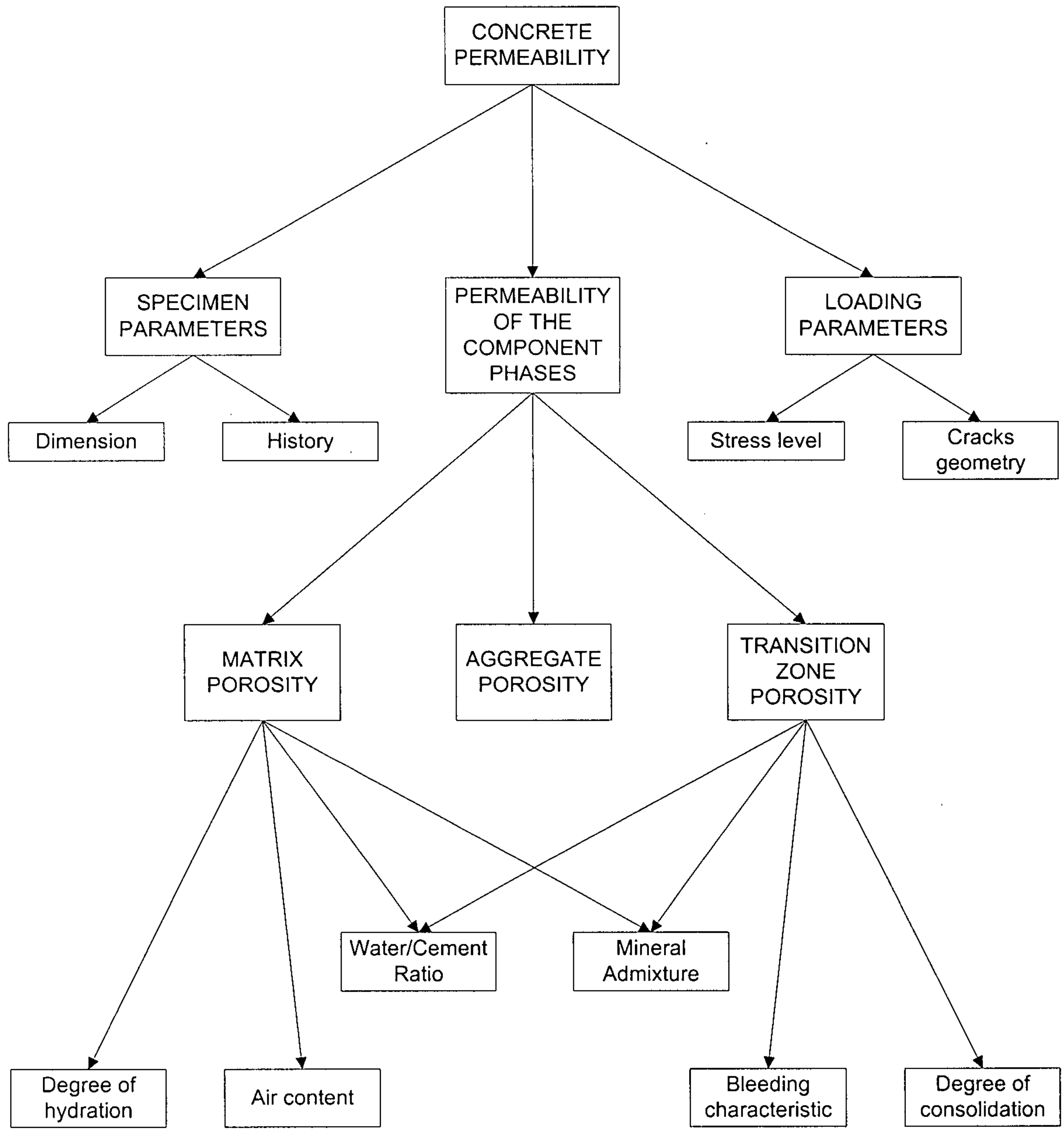


Figure 1.8. **Permeability Parameters [10, with some modification]**

The flow of water within concrete can also have indirect but long-term implications on concrete. When the inflow of water is lower than the outflow, a drying front develops. This can happen internally when the hydration process self-desiccates the concrete or externally when exposed concrete begins to dry out. Lack of water can damage the concrete, especially when young, because it stops the hydration process [18]. Concrete then contracts non-uniformly because only the cement past contracts and the aggregates restrain the contraction and because of moisture gradients.

Water permeation through concrete can affect several characteristics of the material. On a fundamental level, the presence and movement of water affect the hydration process, which control the mechanical properties of the concrete [18]. The permeability of concrete can also be a part of a design specification for structure [19]. More recently, studies have shown that permeability is a key parameter governing long-term durability [20, 21].

Low porosity / permeability / penetrability of concrete to moisture and gas is the first line of defense against: frost damage, acid attack, sulfate attack, corrosion of steel embedment and reinforcements, carbonation, alkali-aggregate reaction, and efflorescence and other concrete ailments [13].

Chemical degradation, e.g. carbonation, corrosion of steel reinforcement, sulfate attack and alkali–aggregate reaction as a result of reaction between an external agent and the ingredients of concrete, and some physical effects, such as frost attack, can be greatly reduced by reducing the permeability of concrete.

1.3 OBJECTIVES AND SCOPE

Until the 1950's, there was no standard test method for measuring the permeation properties of concrete and different laboratories used their own system and setup; however, all techniques are based on the same idea. Place a typical sample between two vessels of different pressure to create a unidirectional flow through the sample, wait for a steady state flow and then measure the rate of flow.

In 1956, the American Petroleum Institute published a standard, which is still in use today (API RP 27 1956). The most widely used method for assessing the permeation properties is ASTM C 1202-97, which is based on chloride ion diffusion and electrical properties of concrete [8]. All existing techniques measure permeability of unstressed concrete, however in real life the concrete are exposed to internal and external stresses. The main objective of the research reported here was:

To develop a test method capable of measuring the water permeability of concrete when it is under an applied stress..

Most of the previous studies were focused on mature concrete, but in this research special emphasis was placed on understanding the influence of stress application on the permeability of concrete at early ages (1-3 days). One can anticipate an even greater increase in the permeability if these loads occur at an early age, when concrete has not yet gained much strength. Early load application, which often occurs in real life, may thus significantly increase the permeability and produce concrete in service with inadequate durability. Furthermore, the effects of fly ash on the permeability of early age concrete have also been studied in this research. Figure 1.9 shows a general overview of this study.

This dissertation contains 7 chapters including: Chapter 1-Introduction and Background, Chapter 2-Concrete Permeability, Chapter 3-High volume fly ash concrete Concrete, Chapter 4-Methods and Materials, Chapter 5-Results and Discussion, Chapter 6-Conclusion and Recommendations, and Chapter 7-References.

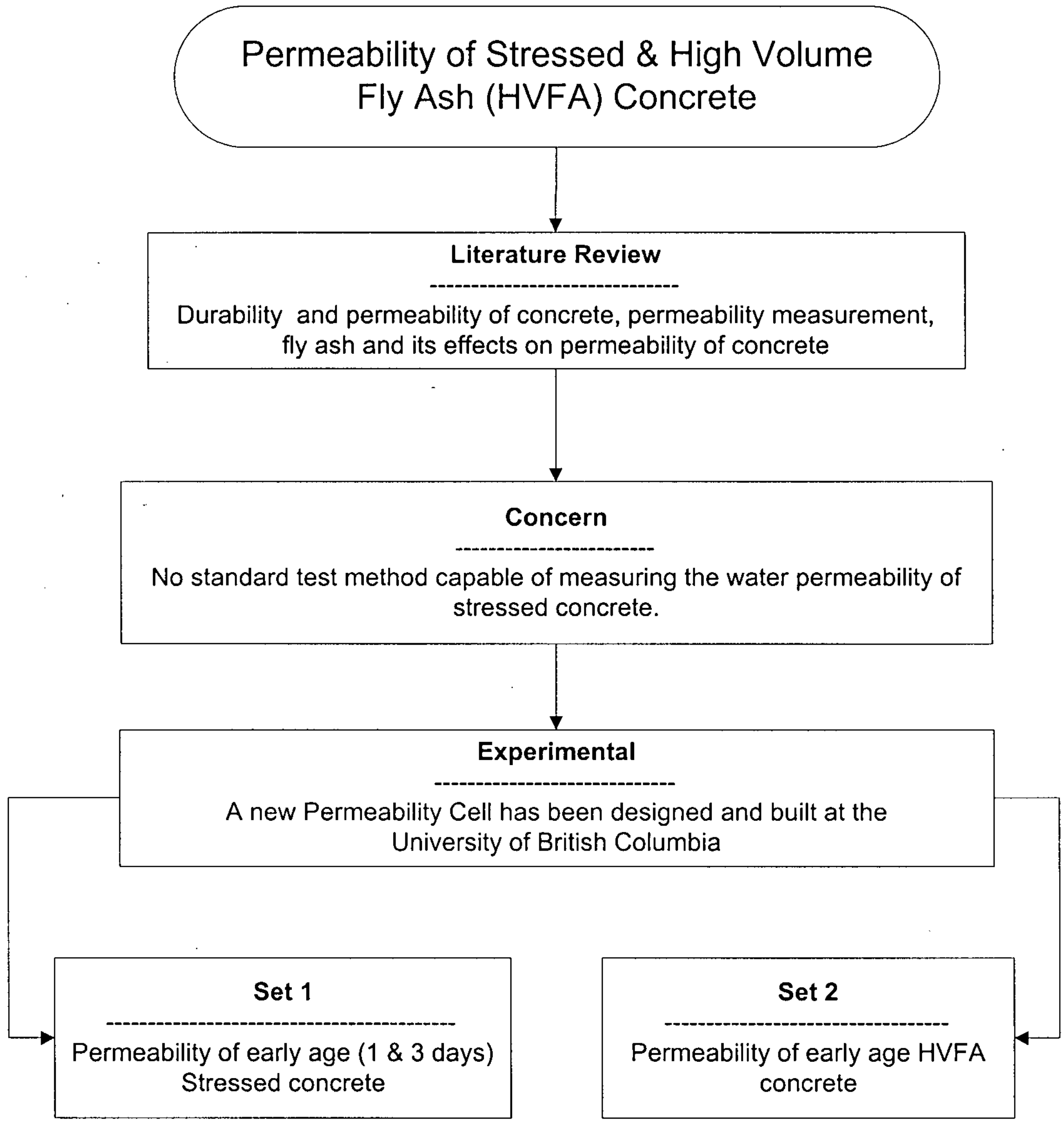


Figure 1.9. **An overview of the program**

CHAPTER 2

CONCRETE PERMEABILITY

2.1 TRANSPORT MECHSNISMS

The transport of fluids into the concrete is due to several mechanisms such as diffusion, permeation, capillary action and absorption. These mechanisms act singly or simultaneously depending on the substance flowing, its local concentration, environmental conditions, the porosity of concrete structure, the radius or width of micro-cracks, the degree of saturation of the pore system, and temperature. This chapter provides a brief summary of these mechanisms.

2.1.1 DIFFUSION

Diffusion is defined as a transfer of mass by random motion of free molecules or ions in the pore solution resulting in a net flow from regions of higher concentration to regions of lower concentration of the diffusing substance. It is a process by which a fluid can pass through concrete under the action of a concentration gradient [22]. For study on deterioration of reinforced concrete structures, ingress of chlorides is one of the most important transport problems associated with movement of the diffusing chloride ion.

The rate of mass transfer through unit area of a section is given by

$$F = dm/dt \,.\, 1/A \qquad \textbf{(Equation 2.1)}$$

where

F = mass flux (g/m^2s)

m = mass of substance flowing (g)

t = time (s)

A = area (m^2)

The Fick's first law of diffusion defines the relation between the concentration gradient dc/dx and the diffusion coefficient D (m^2/s).

$$F = -D \,.\, dc/dx \qquad \textbf{(Equation 2.2)}$$

where

D = diffusion coefficient (m^2/s)

c = concentration (g/m^3)

x = distance or thickness of sample (m)

dc/dx = concentration gradient (g/m^4)

F = mass transport rate (g/m^2s)

For porous solids, the characteristic material property, D, describes the ease of mass transfer by diffusion for a given species through the porous solid. The diffusion coefficient is a function of different variables such as local concentration, concrete age and temperature [8].

2.1.2 CAPILLARY ACTION

Capillary action is defined as transport of liquid in porous solids due to surface tension in capillaries. Characteristics of both solid and the liquid influence it. The characteristics of the liquid that influence capillary action are viscosity, density, and surface tension. The relevant characteristics of the solid include the pore structure, continuity of capillaries and surface energy. Darcy's law modified for non-saturated water flow evaluates the flow of water due to steady state capillary suction [10]:

$$F = k_p / \eta \cdot dp_w / dx \qquad \textbf{(Equation 2.3)}$$

where

F= rate of flow of water (kg/m^2s)

k_p = the coefficient of moisture permeability (kg/m)

η= viscosity of water ($N\ s/m^2$)

dp_w/dx = Pore water pressure gradient (N/m^3)

2.1.3 PERMEABILITY

Permeability is defined as the movement of liquid or gas through a porous medium under an applied pressure head. The permeation of fluids through a porous material due to pressure head is described by the coefficient of gas (K_g) and the coefficient of permeability (K_w). This research is focused on the water permeability.

Water permeability: The coefficient of permeability is a material characteristic, which is given by Darcy's law for laminar flow. Darcy's law is a simple linear equation to describe the transport property.

$$K_w = (Q \cdot l \cdot \eta) / (t \cdot A \cdot \Delta p) \qquad \textbf{(Equation 2.4)}$$

Where

K_w = coefficient of permeability (m^2)

l = thickness of sample (m)

η= dynamic viscosity of liquid (N s/m^2)

t = time (s)

A = cross-sectional area of the sample (m^2)

Δp = decrease in hydraulic pressure through the sample (N/m^2)

The coefficient of permeability (K_w) represents a material characteristic and is independent to the properties of the liquid. But the coefficient of **water** permeability (K_{w*}) is not a material characteristic and describes the flow of water through the material [10]. The following empirical Darcy's formula is described the flow of water:

$$K_{w*} = (Q . l) / (t . A . \Delta h) \qquad \textbf{(Equation 2.5)}$$

K_{w*} = coefficient of water permeability (m/s)

Δh = decrease in hydraulic head through the sample (m)

2.2 PERMEABILITY MEASUREMENTS

Methods of measuring multi-phase transfer in concrete suffer from variability or simplistic modeling divorced from the real environment. That may be the main reason why testing concrete for permeability has not been generally standardized to date. Furthermore, a common feature of most permeability tests is their time consuming nature since each permeameter can only test one sample. Permeability measurements are also subjected to high variability because permeability depends significantly upon specimen conditioning which is hard to qualify and control.

As mentioned, until the 1950's, there was no standard technique for measuring permeability of concrete so reported results from the literature before then are rarely comparable [23]. In 1956, the American Petroleum Institute published a standard, which is still in use today [24]. In 1970, British Standards Institute standardized the Initial Surface Absorption Test (ISAT) method. A gasket cap is either clamped or adhered to the concrete surface. Water is poured into the inlet until the outlet runs clear. A capillary tube is then affixed to the outlet tube, an initial reading is taken and subsequent readings are obtained at 10, 30, 60 and 120 minutes [8].

In the United States the Surface Air Flow (SAF) method proposed by Whiting and Cady [25] has been promoted as an effective measure of relative concrete permeability. In this method a vacuum is created on an approximately 4-in diameter surface of the concrete using a vacuum plate. The pressure inside the vacuum plate is reduced due to the flow of air through the concrete. This change is pressure is monitored with respect to time. The relative permeability of the concrete is determined by the amount of airflow in ml/minute that occurs when the vacuum pressure stabilizes.

Depending on concrete characteristic, there are two major groups of methods for measuring permeability of concrete (Figure 2.1): electrical base and hydraulic base methods.

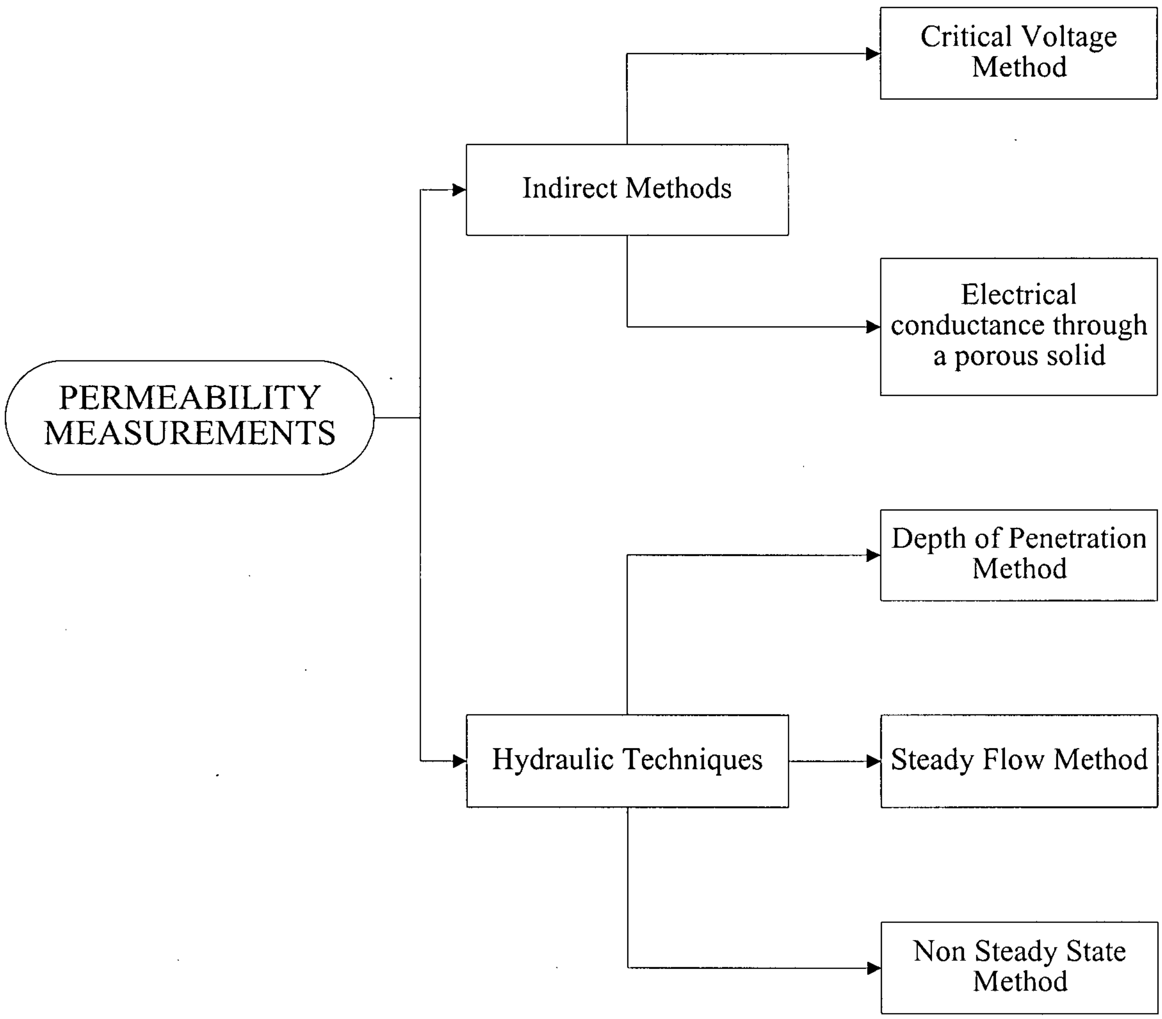


Figure 2.1. **Permeability Measures**

2.2.1 ELECTRICAL BASED METHODS

Some methods employ the electrical and electrochemical techniques to evaluate the permeability of concrete. Several rapid test methods have been established, such as the *critical voltage method* (Figure 2.2). The principle of the critical voltage method is that the current always gets through the weakest path in the materials and the weakest path determines the permeability of concrete.

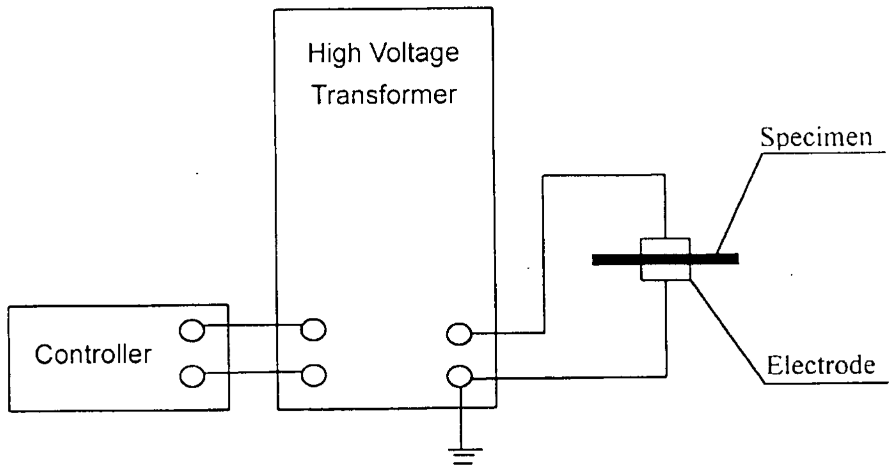


Figure 2.2. **Critical Voltage Method** [26]

The most widely used electrical method for assessing the permeation properties is *ASTM C1202* "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration". This method is the most accepted test to determine the relative permeability of concrete. A 60 V electrical potential is established across a sawed four-inch diameter concrete cylinder section. The total current passing through the section over time and measured in Coulombs is reported as an indication of permeability. Lower Coulomb values indicate lower permeability. The required permeability required is a function of the concrete application [27].

2.2.2 HYDRAULIC BASED METHODS

There are two common practices for evaluating of the permeability of concrete based on hydraulic properties: the depth of penetration method and the steady flow method [3].

The depth of water penetration: test involves subjecting one end of the unsaturated concrete specimen to a pressure head while the other end is free to normal atmospheric conditions. The measure of water penetration is achieved either by measuring the volume of water entering the sample or by splitting the cylinder and measuring the average depth of discoloration due to wetting, taken as equal to the depth of water penetration. Provided that the flow of water is uniaxial, depth of water can be related to the coefficient of permeability equivalent to that used in Darcy's law as below,

$$k = d^2 . v / 2\, h . t \qquad \textbf{(Equation 2.6)}$$

where

d = depth of penetration of concrete (m)

v = the fraction of the volume of concrete occupied by pores

h = hydraulic head (m)

t = time under pressure (s)

The value of v represents discrete pores, such as air voids, which are not filled with water except under pressure, and can be calculated from the increase in the mass of concrete during the test. Bearing in mind that only the voids in the part of the specimen penetrated by water would be considered [3].

$$v = 1000\, M / A . d \qquad \textbf{(Equation 2.7)}$$

where

M = the gain in mass (g)

A = cross sectional area of the sample (mm^2)

d = depth of penetration of concrete (mm)

Steady flow method: these techniques are based on the same principal. Place a typical sample between two vessels at different pressures to create a unidirectional flow through the sample and wait for steady state flow [18]. Under steady state conditions, a value of coefficient of permeability can be determined from the measurements of sample geometry, fluid characteristics, flow rate and the applied pressure. The technique assumes laminar flow through the porous material, applicability of the Darcy's law, and assumption of flow continuity [28].

The steady flow method suits concrete with relatively high permeability, while the depth of penetration method is most appropriate for concrete with low permeability such as high performance concrete.

2.3 FACTORS INFLUENCING PERMEABILITY

Permeability is not only related to the constituents of concrete and the interactions between them but also to the environment and external factors. Some of the main factors that have influence water permeability are explained in this section.

2.3.1 CONCRETE MICROSTRUCTURE

Concrete permeability is determined, in part, by its microstructure, pore structure and presence of cracks. Transportation of fluids through concrete occurs through the network of continuous pores, which exist in the concrete's cementious matrix, as well as the porosity that exist in the interfacial regions with the aggregate. The interconnected porosity governs the transport of fluid and therefore the rate of concrete degradation.

The permeability of concrete is determined by both the total porosity and pore distribution. Porosity is a volume property representing the total void space. It is a function of the original packing of the cement, mineral admixtures, and the aggregate particles, as well as the water-to-solids ratio, the reheology, which is related to the degree of dispersion of the solids originally present, and the curing conditions [16].

During the hydration period, the maturity of the microstructure and the pore architecture depend on the presence of water. Water must always be available to complete the hydration process, either from the time of mixing or from an external source that is accessible to the open pores. Hence, the degree of hydration controls many characteristics of concrete, such as strength, stiffness, and transport properties.

The hydration process is a chemical reaction that hardens and strengthens the material. This process slows down with time but continues for months and even years. As hydration progresses, the microstructure of the porous body also changes. Most importantly, the porosity decreases. The microstructure can be controlled by many factors, including the water-cement ratio, the curing temperature, and the type of Portland cement [18].

As mentioned, the microstructure of the porous body governs its transport properties. The solid phase is composed of hydration products and unhydrated cement grains. The hydration products include the gel, (C-S-H) plus crystalline components such as $Ca(OH)_2$. The gel contains a 28% porosity. These gel pores are 2-3 nm in nominal diameter only an order of magnitude larger than a molecule of water [19], so gel water is tightly bound and not mobile.

The space originally filled by mix water is called capillary porosity. Capillary pores are typically one to two orders of magnitude larger than gel pores. Water added to concrete is distributed in three ways, chemically incorporated into the hydration products, water tightly held as gel water, or retained as free water [18]. The excess mix water that is not used for hydration or absorption forms the capillary pores. Therefore, the greater the amount of excess water, the greater the capillary porosity. The volume of capillary porosity increases with increasing w/c ratio and decreases with increasing degree of hydration, as hydration products gradually fill them.

The interconnected capillary pores dominate the transport properties of cement paste. As hydration progresses, the capillary pores become segmented and may be connected only by gel pores. Since these pores are so small and water in them is so tightly bound, the permeability decreases dramatically. Capillary porosity decreases as cement paste matures, and hydration products deposit in the capillary pores; the capillary pores can depercolate. Powers [29] performed a volumetric calculation for a closed system and concluded that, even when the cement is fully hydrated, capillary pores still exist, although possibly disconnected, unless w/c<0.35. At the other extreme, when w/c>0.7, capillary pores are never fully depercolated.

2.3.2 CONCRETE CURING

Concrete curing can be defined as a group of actions employed to make available an environment in which sufficient hydration of cementious materials can occur. The objective of curing is to keep the concrete near saturation, sealing the moisture in until the voids that were filled with water are filled with hydration products to achieve the desired properties. The two major categories used to describe concrete curing methods include membrane curing and wet (or moist) curing. Membrane curing seals the concrete surface by the application of membrane-forming chemical compounds. Moist curing requires that the surface of the concrete be in continuous contact with water and may be achieved by ponding or flooding, covering wet concrete with earth or straw, or the use of a wet burlap blanket. The type of curing method used is dependent upon several factors including water availability, environmental conditions and the geometric constraints. Curing time is also a major factor when using the moist curing method. The length of curing is depended upon the severity of the drying conditions and the desired hardened concrete properties [8].

Several investigators have discussed the effect of concrete curing time on the development of strength and permeability [30, 31]. These researchers found that strength increases and permeability decreases with increased moist curing time. Interestingly, sufficient strength may be achieved in a concrete element without proper curing but the durability may be inadequate [32]. Near the surface concrete may develop a coarse interconnected pore structure due to improper curing conditions, which directly affects its permeability.

The influence of humidity during curing on concrete permeability is, furthermore, probable as a result of micro cracking in the transition zone caused by drying shrinkage. Also, when concrete is fresh and water evaporates faster than it can reach the top surface, it can create plastic shrinkage cracking. Hence, proper curing condition is vital for long-term durability of concrete.

2.3.3 SUPPLEMENTARY CEMENTIOUS MATERIALS

Various mineral admixtures are being widely used to improve concrete durability. Pozzolanic materials such as fly ash, slag are now being widely used to enhance concrete properties. Experts have widely agreed for decades that the use of pozzolans under proper condition and curing can reduce concrete permeability by seven to ten times [13].

In particular pozzolan and its role can be viewed as having two principal aspects. First, the use of a high quality pozzolan will result in a denser cement paste matrix. Second, pozzolans react with lime produced in the hydration reaction and form a binder. The additional binder resulting from this pozzolanic reaction provides a low permeability and high-strength matrix. Furthermore, lime accumulates at the interface between the matrix and the aggregate, reacts with pozzolanic material in these regions and creates dense transition zones with enhanced properties.

2.3.4 APPLIED STRESS

The influence of an externally applied stress on the permeability of concrete remains poorly understood. For mature concrete, while Hearn [34] found no appreciable effect of stress on the water permeability, Kermani [35] found that permeability increased significantly when the stress level exceeded 40% of the ultimate strength. A primary difference between these two studies was that Hearn [34] had subjected the specimens to stress prior to carrying out the permeability tests whereas in Kermani's study [35], permeability tests were carried out in the presence of an applied stress. Indeed, when Hearn and Lok [36] carried out nitrogen permeability tests while maintaining a stress on concrete, they too found that there is a threshold value of stress beyond which increases in the permeability occurred.

One can anticipate an even a greater increase in the permeability if these loads occur at an early age, when concrete has not yet gained much strength. Early load application, which often occurs in real life, may thus significantly increase the permeability and produce concrete in service with inadequate durability. Little or no understanding exists of the influence of early loading on permeability.

CHAPTER 3

HIGH VOLUME FLY ASH CONCRETE

3.1 INTRODUCTIONS AND BACKGROUND

Fly ash closely resembles the volcanic ashes used in the creation of the earliest known hydraulic cements some 2,300 years ago, near the small Italian town of Pozzuoli. The volcanic ashes were used in a number of well-known Roman structures including the Coliseum, Pantheon, and Aqueducts, which survive to date (Figure 3.1 and 3.2).

In the early days of the power generation industry, coal combustion products were considered to be waste materials. The properties of these materials were not studied or evaluated seriously and almost all of the coal combustion products were land filled (Figure 3.3). In the 1920's, more effective methods of firing power plant boilers were invented. These new processes involved burning pulverized coal instead of lump coal. While the process was a more efficient method of firing, the process generated increased amounts of fine combustion products and lower quantities of cinders. This fine combustion product is called fly ash, and the cinders that are relatively finer are called bottom ash [40].

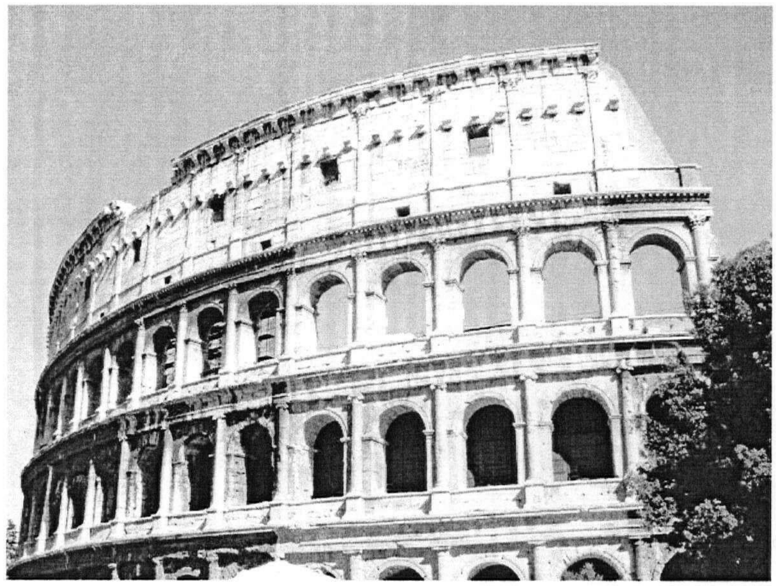


Figure 3.1 **Coliseum Rome [41]**

Figure 3.2 **Pantheon Rome [42]**

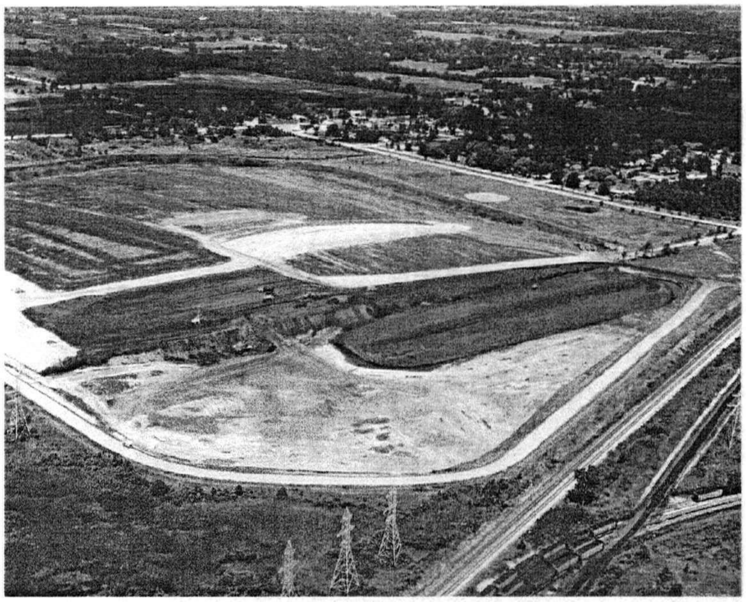


Figure 3.3 **Coal ash Landfill in Oak Creek [40]**

Fly ash concrete was first used in the U.S. in 1929 for the Hoover Dam. Later, between 1948 and 1953 about 120,000 metric tons of fly ash were used in the construction of Hungry Horse Dam in Manitoba (Figure 3.4).

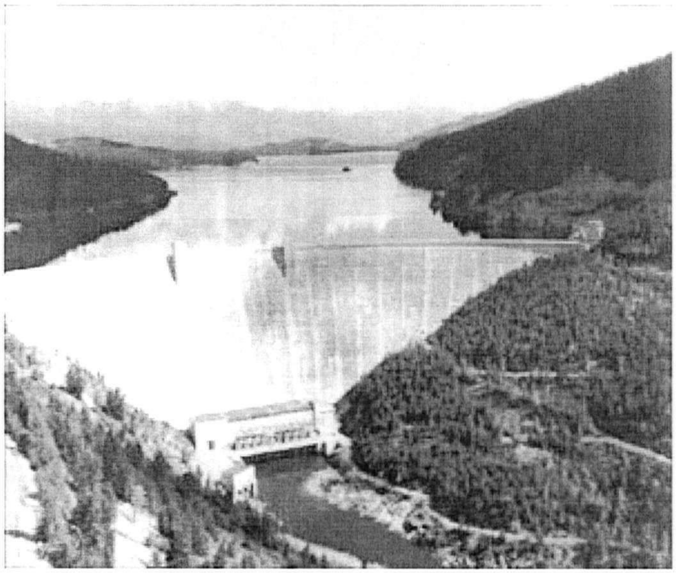


Figure 3.4. **Hungry Horse in Manitoba [43]**

Fly ash was introduced commercially in the Lower Mainland during the 1970s and was typically used to replace about 10% of the Portland cement in a concrete mix. There was some resistance in the construction industry initially, but by the early 1980s the benefits were better understood and replacement percentage of fly ash increased to 15-20%. Larger percentages were used occasionally, mainly for mass concrete - first 30% and then up to 40% fly ash. In the 1990s, 20% fly ash replacement became common for structural concrete, and up to 40% for mass concrete. In the 2000s, more and more engineers are looking to use 40-60% fly ash in structural concrete [44].

The world generation of fly ash is more than 500 M tonnes annually and is projected to increase significantly. It is estimated that globally only about 20% of the available fly ash is being used by the cement and concrete industry [45].

Canada produces about 5 M tonnes annually, of which about 10% is currently used as a supplementary cementing material (SCM). Much of this use is in Western Canada, where the properties of available fly ash are appropriate as a premium SCM. British Columbia, which produces about 1 M ton of cement per year, produces no fly ash but currently uses about 160,000 tonnes annually sourced from Alberta (where four coal-fired plants produce about 2.7 M tones annually, of which about 25% is used in various forms including SCMs) or from Centralia, Washington [46].

In general, using fly ash is a solution for having a sustainable concrete industry. For a variety of reasons, the concrete construction industry is not sustainable. First, it consumes huge quantities of virgin materials. Second, the principal binder in concrete is Portland cement, the production of which is a major contributor to greenhouse gas emissions that are implicated in global warming and climate change. Third, many concrete structures suffer from lack of durability which has an adverse effect on the resource productivity of the industry [45]. Because the high-volume fly ash concrete system addresses all three sustainability issues, its adoption will enable the concrete construction industry to become more sustainable which in turn will improve concrete quality (Figure 3.5).

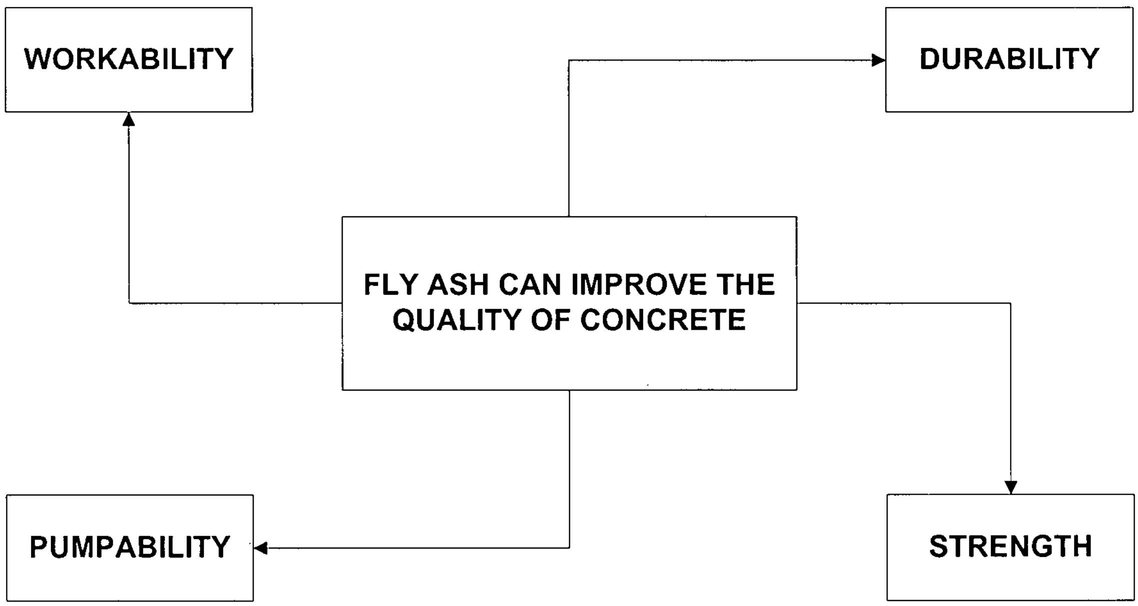


Figure 3.5. **Quality Improvement**

3.2 FLY ASH CLASSIFICATIONS AND CHEMICAL REACTION

Fly ash has been classified into two classes, F and C, based on its chemical composition. The chemical requirements to classify any fly ash are shown in Table 3.1.

Table 3.1. **Chemical Requirements for Fly Ash Classification [47]**

Properties	Fly Ash Class	
	Class F	Class C
Silicon dioxide (SiO_2) plus Aluminum Oxide (Al_2O_3) plus Iron Oxide (Fe_2O_3), min, %	70.0	50.0
Sulfur Trioxide (SO_3), max, %	5.0	5.0
Moisture content, max, %	3.0	3.0
Loss on ignition, max, %	6.0	6.0

Class F Fly Ash

Class F fly ash is produced from burning anthracite and bituminous coals. This fly ash has siliceous or siliceous and aluminous material, which themselves possesses little or no cementitions value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form cementitious compounds. This class reduces bleeding and segregation in fresh concrete. In hardened concrete, it increases the ultimate strength and reduces drying shrinkage, permeability, and heat of hydration [48].

Class C Fly Ash

Class C fly ash is produced normally from lignite and sub-bituminous coals and usually contains significant amount of Calcium either as lime or other minerals. This class of fly ash, may have very little pozzolanic properties, but has cementitious properties (ASTM C 618-99). Class C Fly Ash provides exclusive self-hardening characteristics and improves permeability. It is particularly valuable in pre-stressed concrete and other applications where high early age strengths are necessary [49].

Creation of cementitious material by the reaction of free lime with the pozzolans (Al_2O_3, SiO_2, Fe_2O_3) in the company of water is known as hydration. The hydrated calcium silicate gel or calcium aluminates gel (cementitious materials) can bind inert materials together. For class C fly ash, the calcium oxide (lime) of the fly ash can react with the siliceous and aluminous materials (pozzolans) of the fly ash itself. Since the lime content of class F fly ash is relatively low, addition of lime is necessary for hydration reaction with the pozzolans of the fly ash. For lime stabilization of soils, pozzolanic reactions depend on the siliceous and aluminous materials provided by the soil. The pozzolanic reactions are as follows:

$$Ca(OH)_2 \Rightarrow Ca^{++} + 2[OH]^-$$

$$Ca^{++} + 2[OH]^- + \underset{\text{(silica)}}{SiO_2} \Rightarrow \underset{\text{(gel)}}{CSH}$$

$$Ca^{++} + 2[OH]^- + \underset{\text{(alumina)}}{Al_2O_3} \Rightarrow \underset{\text{(gel)}}{CAH}$$

Hydration of tricalcium aluminate in the ash provides one of the primary cementitious products in many ashes. The rapid rate at which hydration of the tricalcium aluminate occurs results in the rapid set of these materials, and is the reason why delays in compaction result in lower strengths of the stabilized materials [48,49].

Canadian Classification

This classification is based on Calcium content of the fly ash. Class F is low calcium content fly ash with less than 8% of CaO. Class C fly ash has higher calcium oxide content than Class F ash and is divided into two types, type CI and type CH. The calcium content of type CI is more than type F but is less than 20%. Type CH has more than 20% of CaO (Table 3.2).

Table 3.2. **Fly Ash Classification in Canada**

Type	CaO
F	< 8 %
CI	8 – 20 %
CH	> 20 %

3.3 APPLICATION

The initial coal combustion products were called cinders and were used as road gravel and sometimes as a lightweight aggregate in manufacturing masonry "cinder" blocks. In the course of time, the cementitious and pozzolanic properties of fly ash were recognized and studied [40].

High-volume fly ash concrete was first developed for mass concrete applications where low-heat generation was required. Later it was demonstrated that this type of concrete, given its excellent mechanical and durability properties, can also be used for structural applications (Figure 3.6) and for pavement construction. Today, fly ash is used in shotcrete, lightweight concrete and roller-compacted concrete, etc. From a repair point of view, using fly is a new way to increase the long-term bond strength of new-to-old concrete.

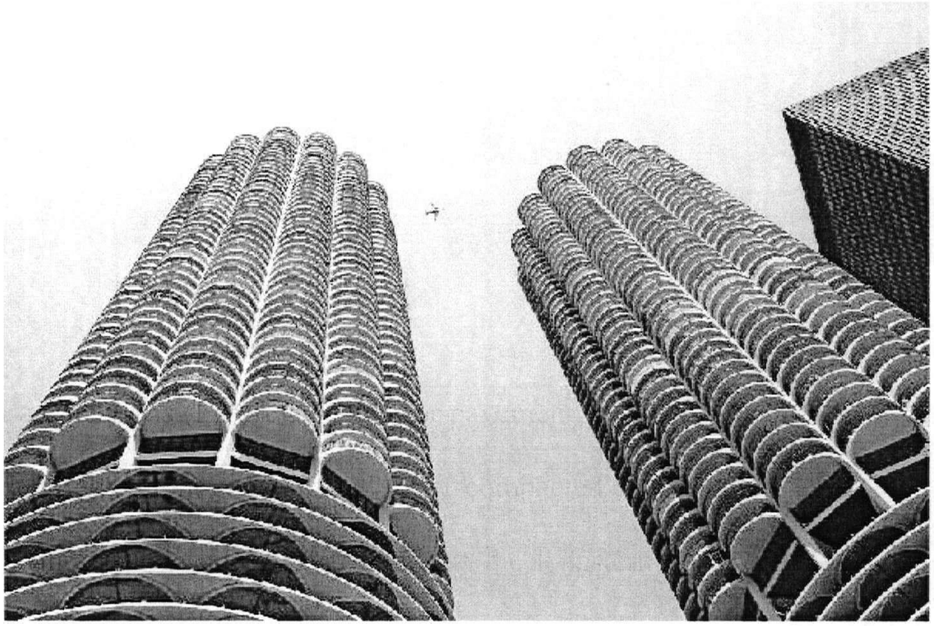


Figure 3.6. **Fly Ash Concrete in Chicago [51]**

Fly ash can be used by the cement and concrete industry as a source of raw material in cement production, co-ground with clinker and gypsum in blended cement, and as a supplementary cementing material. As a supplementary cementing material, fly ash is used in two different ways in concrete:

1-partial replacement of cement with fly ash

2-the use of fly ash partially with cement and aggregate

At the present time fly ash is used as a material by construction industry in Canada in different areas (Figure 3.7).

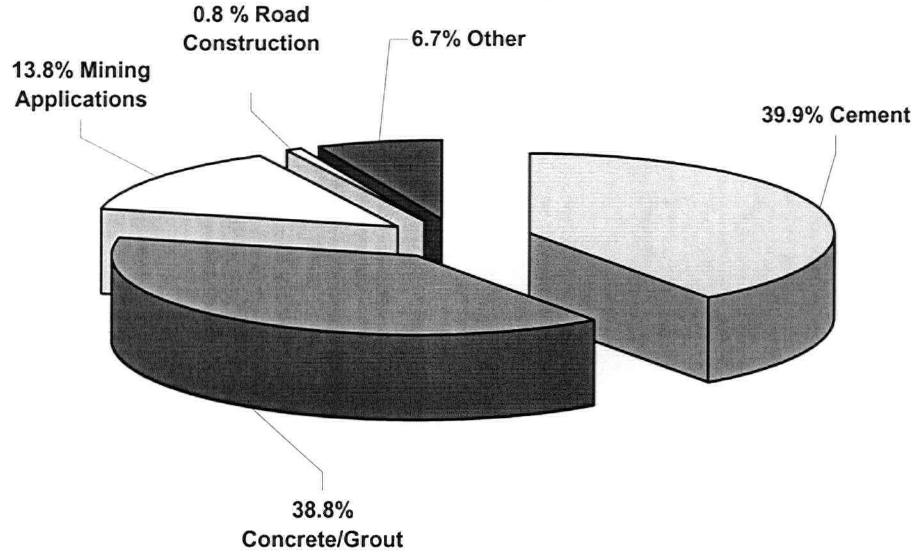


Figure3.7. **Use of Fly ash by the Construction Industry in Canada [52]**

3.3 DURABILITY OF HVFA CONCRETE

Several laboratory and field investigations involving cements and fly ashes from various sources around the world have demonstrated the excellent durability of high-volume fly ash concrete [50]. These investigations show that following proper curing the use of pozzolanic materials with proper quality and correct quantity has a positive influence on concrete durability.

Well cured concrete containing a large amount of fly ash not only gives very low permeability and fewer cracks due to thermal and drying shrinkage effects, but also provides excellent protection against expansive chemical reactions, such a sulfate attack and the alkali-silica reaction [53].

Fly ash also reduces heat of hydration and water demand, densifies transition zone and in turn improves the durability of concrete (Figure 3.8).

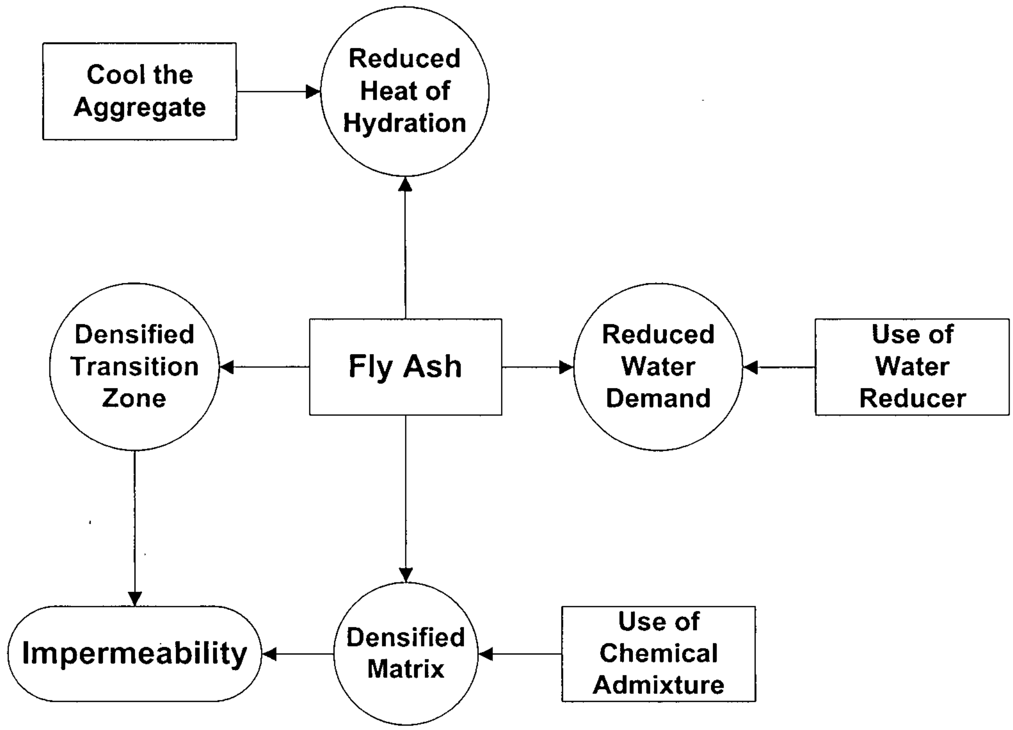


Figure 3.8. **Holistic Performance of Fly Ash for Concrete Durability [66, with some modification]**

3.4 PERMEABILITY OF HVFA CONCRETE

Permeability of concrete is greatly influenced by the water cement ratio, curing condition, and cracking resistance of concrete. As mentioned, adding fly ash under proper curing condition, provides excellent water-tightness in concrete. When Portland cement hydrates, it forms calcium-silicate hydrate gel CSH and calcium hydroxide Ca $(OH)_2$. Calcium-silicate hydrate is the "glue" that provides strength and holds the concrete together. Compared to Ca $(OH)_2$, CSH contributes more to strength, and impermeability. Permeability is related to the proportion of calcium-silicate hydrate to calcium hydroxide in the cement paste. The higher the proportion of calcium-silicate hydrate to calcium hydroxide, the lower the permeability of the concrete.

The interfacial transition zone between the aggregate and cement paste is the area with high water cement ratio and therefore with higher percentage of calcium hydroxide. Fly ash with different mechanism can improve impermeability by different mechanisms. First of all, when fly ash is used as part of the cementitious material in a concrete mixture, it reacts with calcium hydroxide to form additional calcium-silicate hydrate, which in turn lowers the permeability of the concrete. Also the use of a pozzolan like fly ash tends to decrease the formation of interfacial transition zone [54].

Second, fly ash is a fine material with spherical shape (Figure 3.9 and 3.10) that improves the workability and can act as a water reducer. With reducing the water content, not only the weak link in concrete is strengthened but also the porosity of cement paste is decreased. Clearly the water-reducing property of fly ash can be advantageously used for achieving a considerable reduction in the drying shrinkage and cracking.

Hence, fly ash with combination of particle packing effects, reduced water demand, and pozzolanic reaction can develop an impermeable mature concrete.

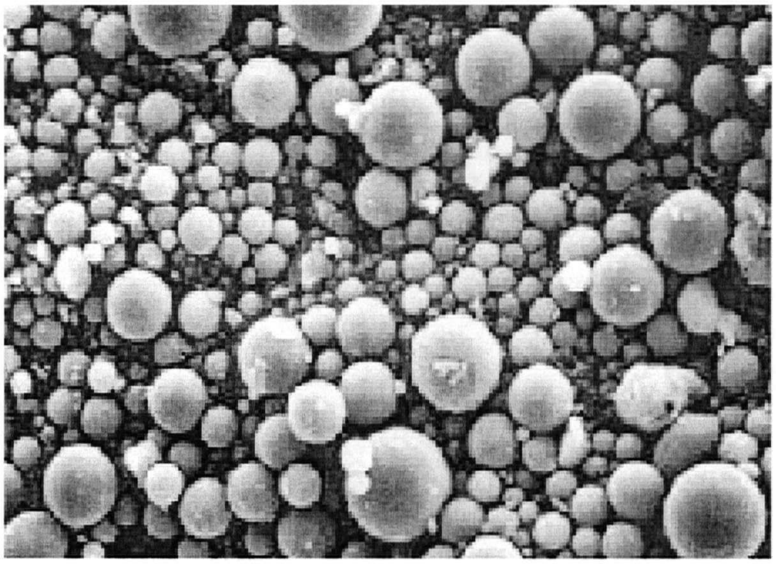


Figure 3.9. **Fly Ash Consists of Spherical and Glassy Particles [55]**

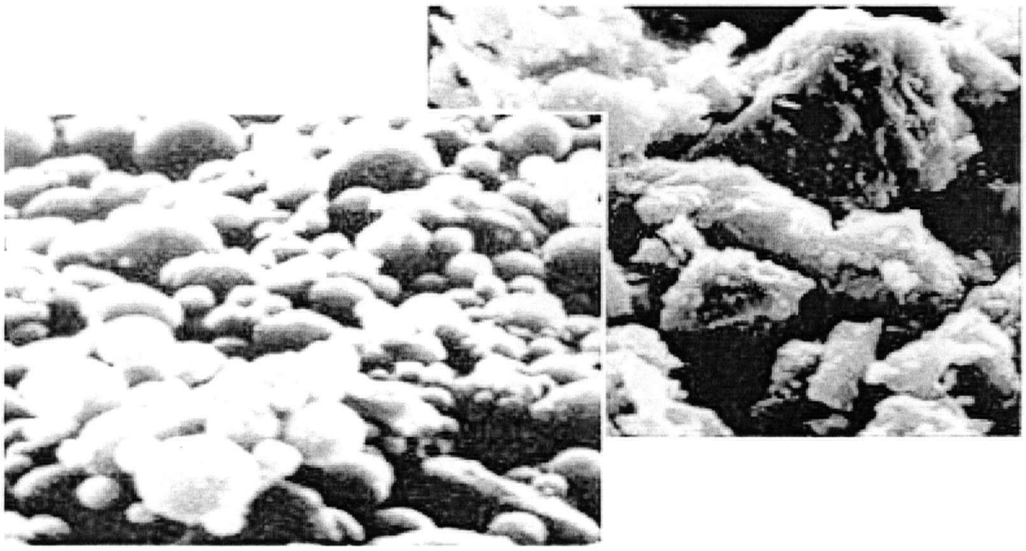


Figure 3.10. **Comparison between Fly Ash (Left) and Cement (Right) Particles [55]**

CHAPTER 4

METHODS AND MATERIALS

4.1 PERMEABILITY OF CONCRETE UNDER STRESS

As mentioned, the main goal of this research was to develop a test method capable of measuring the water permeability of stressed concrete. In the first part of the research, the effects of stress and age on concrete permeability were investigated. The second part the effects of fly ash on the permeability of concrete have been studied.

4.1.1 CONCRETE MIXTURES AND MATERIAL

The mixed proportions of concrete used in this test program are given in Table 4.1. CSA Type 10 normal Portland cement (ASTM Type I), coarse aggregate with a maximum size of 9.5 mm, saturated surface-dry (SSD) clean river sand with a fineness modulus of about 2.5 and potable water were used.

Table 4.1 **Concrete Mix Proportions (Set 1)**

Ingredient	Quantity
Cement	250 kg/m^3
Water/ Cement	0.60
Water	150 kg/m^3
9.5 mm Aggregate	950 kg/m^3
Sand	950 kg/ m^3

4.1.2 TEST SPECIMENS

The objective of the research was to investigate the permeability of stressed concrete. To achieve this objective, cylindrical specimens 102 mm diameter x 204 mm height (4"x 8") were used to determine the compressive strength and hollow cylinders (Figure 4.1) were used to obtain the permeability of concrete. Three 102 x 204 cylinders and two hollow 102 x 204 cylindrical specimens were tested per concrete mixture.

Aggregate, sand and cement were dry mixed together in a pan mixer and water was added followed by mixing for a few minutes. Normal PVC molds were used for casting cylindrical specimens, however two special molds were used to make the hollow cylinders. These molds consist of four main parts: the lower part, body, upper ring and a core (Figure 4.2). For regular cylindrical molds, oil was used to make demolding easier, but for hollow mold cylindrical molds to prevent the effects of oil on concrete permeability, no lubricants were used.

Figure 4.1. **Hollow Core Concrete Cylindrical Specimens**

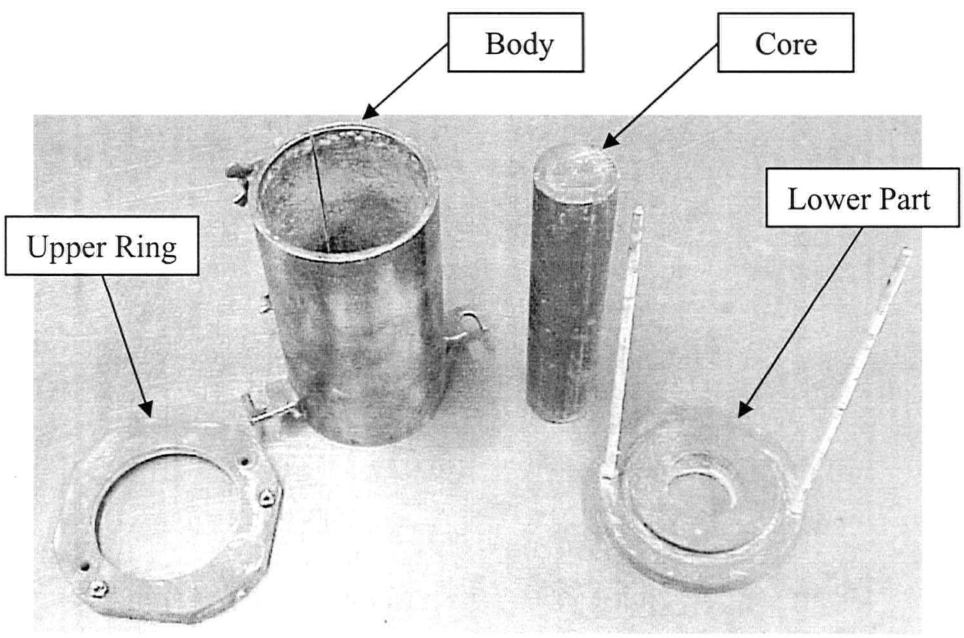
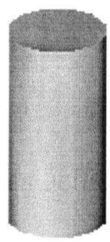
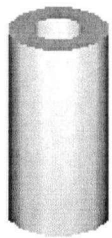


Figure 4.2. **Permeability Mold Components**

Consolidation was achieved using a table vibrator. Test specimens were cast and allowed to achieve their initial set before covering them with plastic sheets. As mentioned earlier, for each of the four investigated mixes, three cylinders and two hollow cylinders were cast (Table 4.2).

Table 4.2. **Specimens Information**

SPECIEMN TYPE	DETAILS
	Dimension, **102 mm x 204 mm** Quantity, **Three Per Mix** Test, **Compressive strength** **(1 and 3 days) ASTM C39**
	Dimension, **102 mm x 204 mm** Inside Diameter, **50 mm** Quantity, **Two Per Mix** Test, **Permeability Test** **(1 and 3 days)**

Demolding of the specimens took place 24 hours after casting. For regular cylindrical samples, the mold was removed using air pressure, but for hollow samples hydraulic pressure was applied to remove the molds. First, the internal core and then the body were removed. The samples were moved into the saturated limewater bath until the day of testing.

4.1.3 UBC PERMEABILITY CELLS (UPC)

Since test procedures for measuring the permeability of water under stress are not standardized, a test device was designed and constructed. Based on this study requirements the following designs were considered (Figure 4.3) and finally the last design was adopted (Figure 4.4). The UBC permeability cells (UPC) were designed such that a constant hydraulic pressure could be applied to the outside walls while the inner wall remained free under atmospheric pressure. The UPC comprises three main parts: cell, water supply, and the measuring device.

The cell consists of two 1400 x 1400 x 45 mm thick top and bottom aluminum plates, a 160 mm diameter aluminum tube, a 50 mm diameter piston, and a 100 mm diameter aluminum upper disk. Major components of the cell are shown in Figure 4.5. The cell components are tightly secured together by four studs and four nuts while two O-rings were installed between the tube and the plate to provide a watertight sealing.

The water supply is an aluminum cylinder with two aluminum plates on its ends. The driving pressure is controlled by a regulator and kept constant throughout the test period, thus eliminating one of the major factors that cause uncertainty in the permeability test results.

The measuring device is a computer-controlled scale that continuously and accurately measures the drained out flow with 0.01gram accuracy.

Two permeability cells were built at the University of British Columbia. One cell is mounted in a Universal Testing Machine such that a compressive stress can be applied on the specimen. The other identical cell is placed outside of the Universal Testing Machine such that the specimen therein is under zero stress (Figure 4.6).

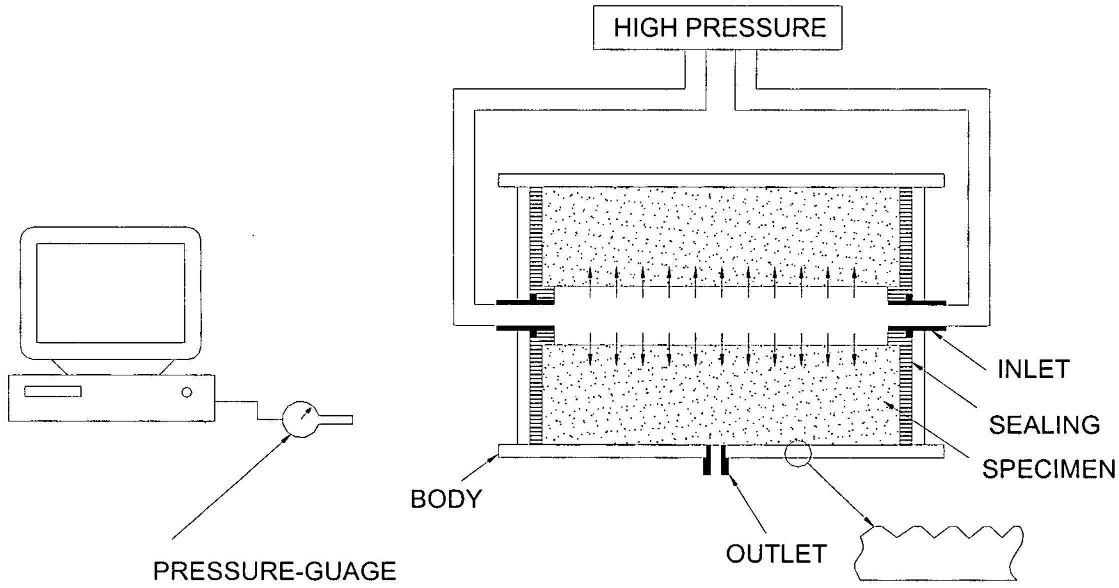


Figure 4.3 a

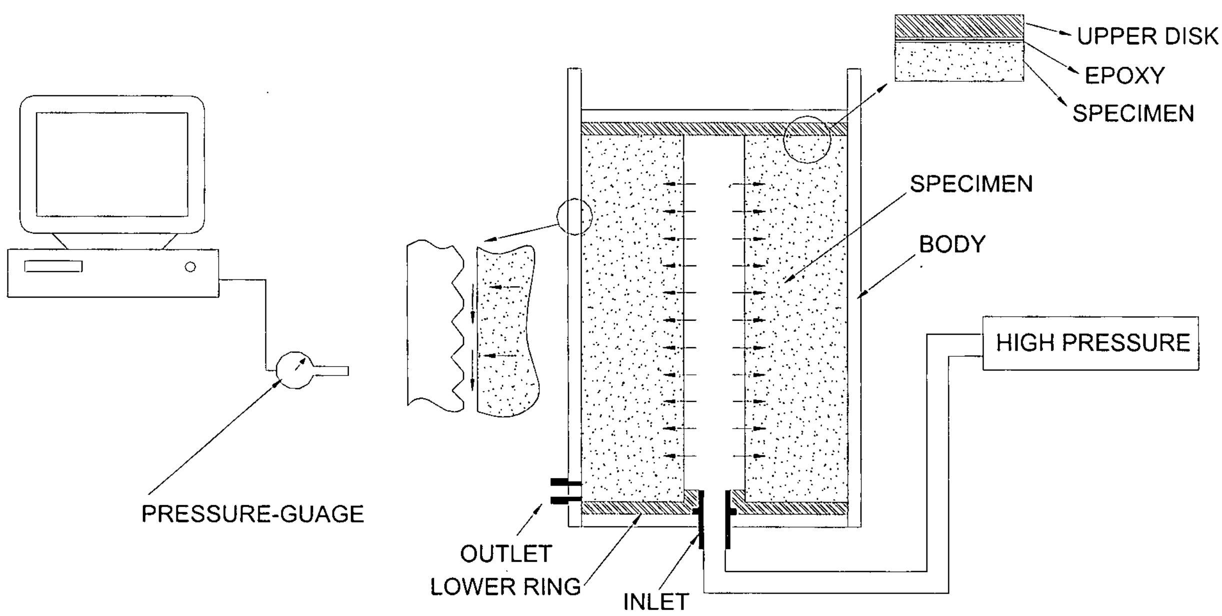


Figure 4.3 b

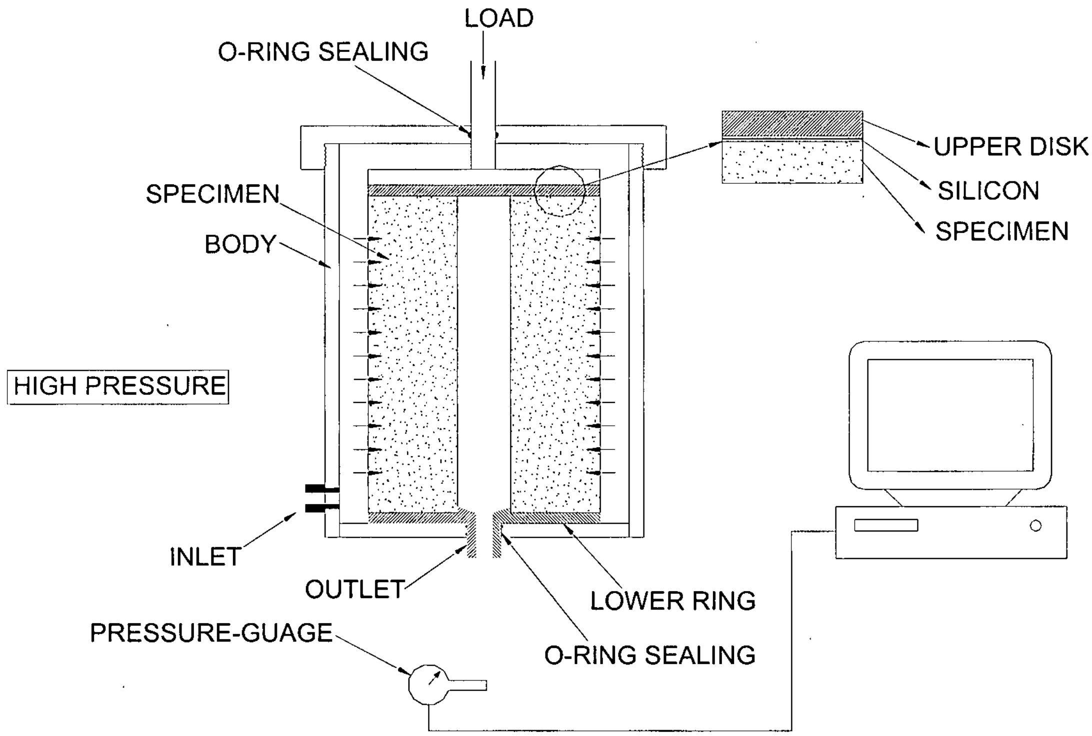


Figure 4.3 c

Figure 4.3. **Permeability Cell (a) First design was not accepted because no stress could be applied. (b) Second design, was not accepted because no stress could be applied and the wet area must be maximized. (c) Third design was not accepted because the high accuracy pressure gauges were too expensive.**

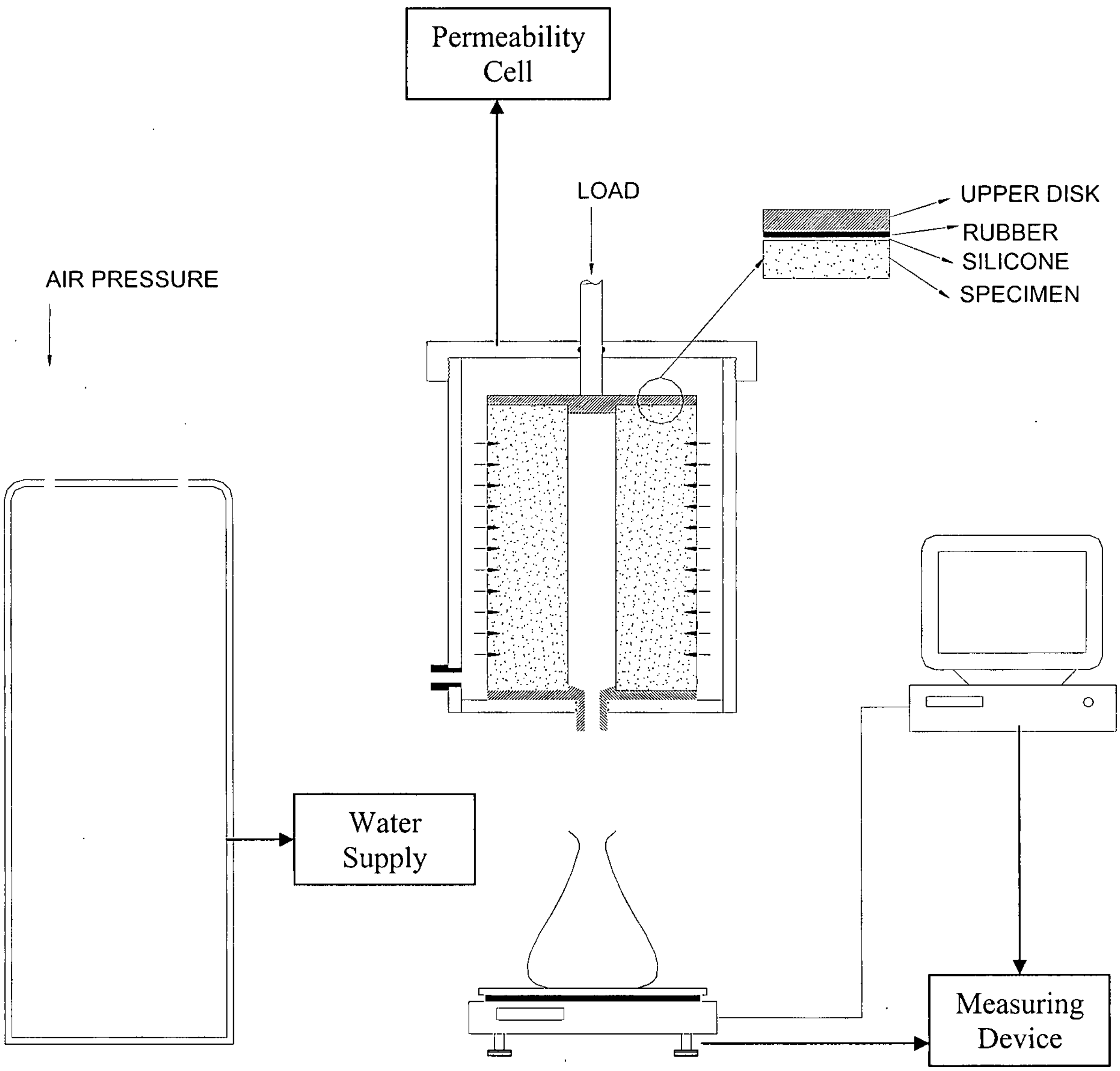


Figure 4.4. **Schematic of Permeability Test Setup**

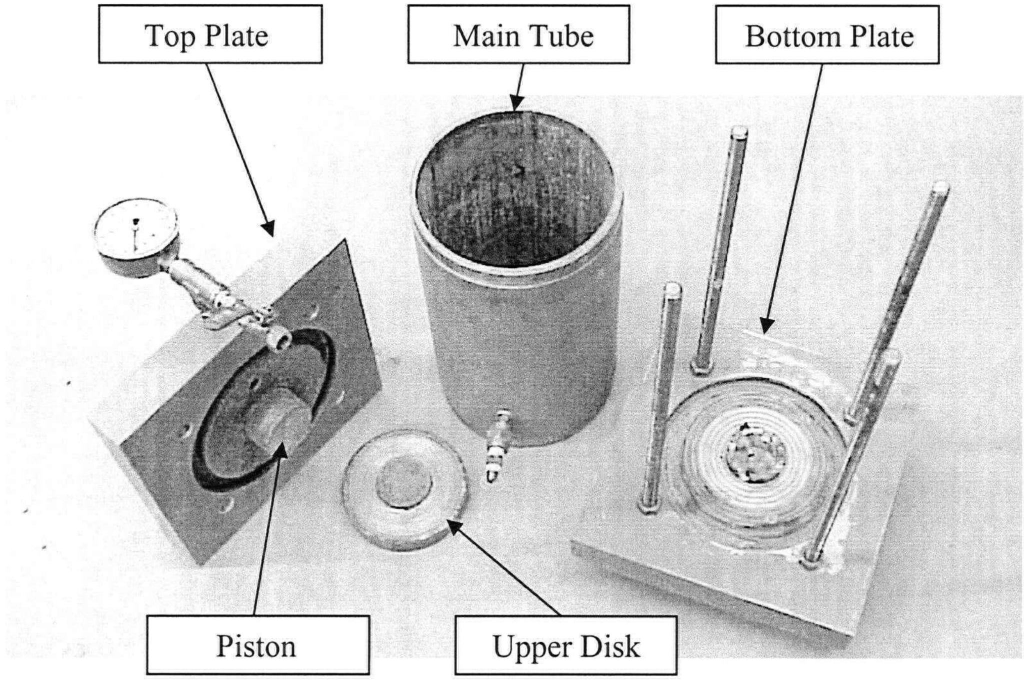


Figure 4.5. **Permeability Cell Components**

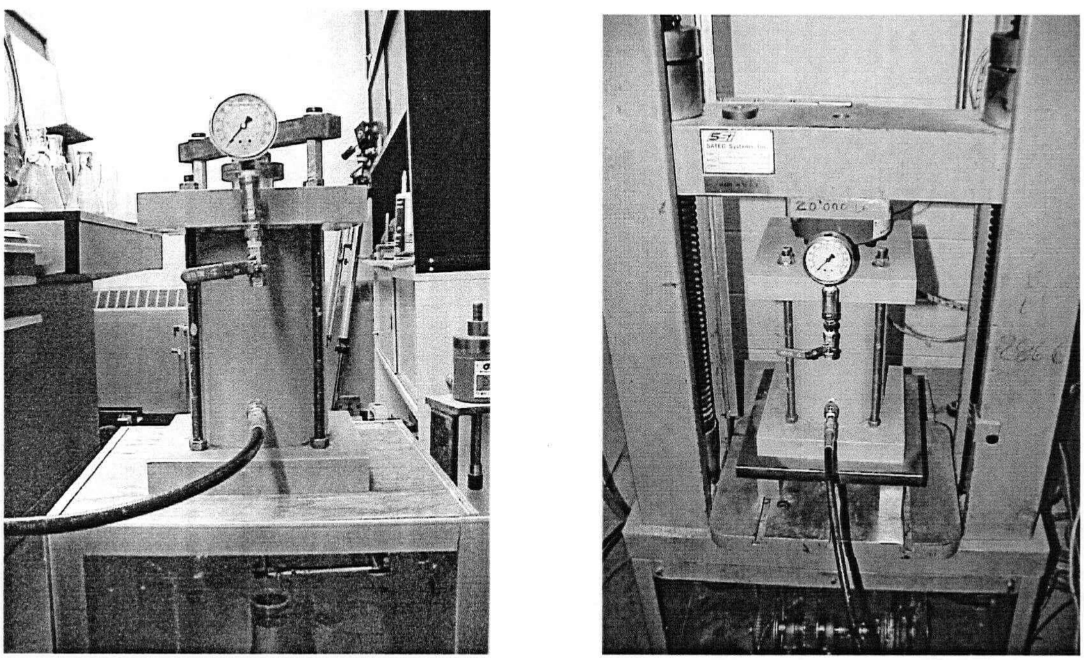


Figure 4.6. **Left: UBC Permeability Cell (UPC) and Right: The Cell in a Universal Testing Machine**

4.1.4 TEST PROCEDURE

Sample Preparation- Some specimens were tested at an age of 24 hours after being cured under a plastic sheet. The next set of specimens were 3 days old at the time of test and were cured in lime-saturated water for 2 days. The first step of specimen preparation was grinding the ends which created two parallel planes. Water was used as the cooling fluid during grinding. Grinding was a major concern, especially for one day old specimens, because the samples did not have enough strength and could easily be damaged (Figure 4.7). To solve this problem, an aluminum ring was placed at the top of the mold when concrete was poured. This ring smoothed the top surface of the sample, which in turn made the grinding possible with minimum damage.

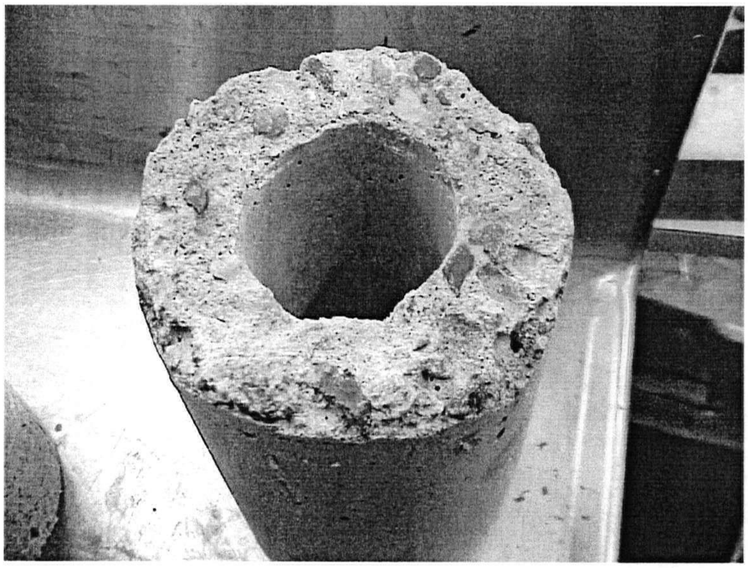


Figure 4.7. **Damaged Specimen after Grinding**

Sealing- In any permeability test on concrete, a key requirement is to prevent boundary leakage around the sample. In this study, rubber rings and concrete silicone (DOW 790 and DOW 795) were used for this purpose. Top and bottom surfaces of the hollow cylinder were cleaned and dried, and then two-rubber rings (2" inside diameter, 4"outside diameter, and 2 mm thickness) were placed on these surfaces using silicone. This sample was then allowed to dry for an hour.

Assembling- The sample was placed into the cell in such a way that the bottom surface of the sample sat on the bottom plate of the cell. The upper ring was placed on the top of the sample and the top plate of the cell was clamped tightly in order to squeeze the upper disk inside the cell and prevent leakage of water through the sealing between the sample and the disk.

Next, the cell components were tightly secured together by four studs and nuts. One cell was mounted in a Universal Testing Machine such that a compressive stress could be applied on the specimen. The other cell, identical in design, was placed outside of the Universal Testing Machine such that the specimen therein carried zero stress. Finally, the water supply pipes were connected to the cells (Figure 4.8).

The last step before running the test was to determine the amount of load to be applied to the specimen. As mentioned earlier, the main objective of the research was to investigate the effects of stress on the permeability of concrete. For this purpose a percentage of ultimate load (20%, 30% and 40%) was applied on the specimen. Hence, the ultimate strength of concrete had to evaluated before running the test. Compressive strength of the samples was determined by crushing three samples from each batch. Figure 4.9 shows the compression test machine used in this study with a capacity of

600,000 lb (2650 kN). Compressive strength tests were conducted in accordance with ASTM C 39-96.

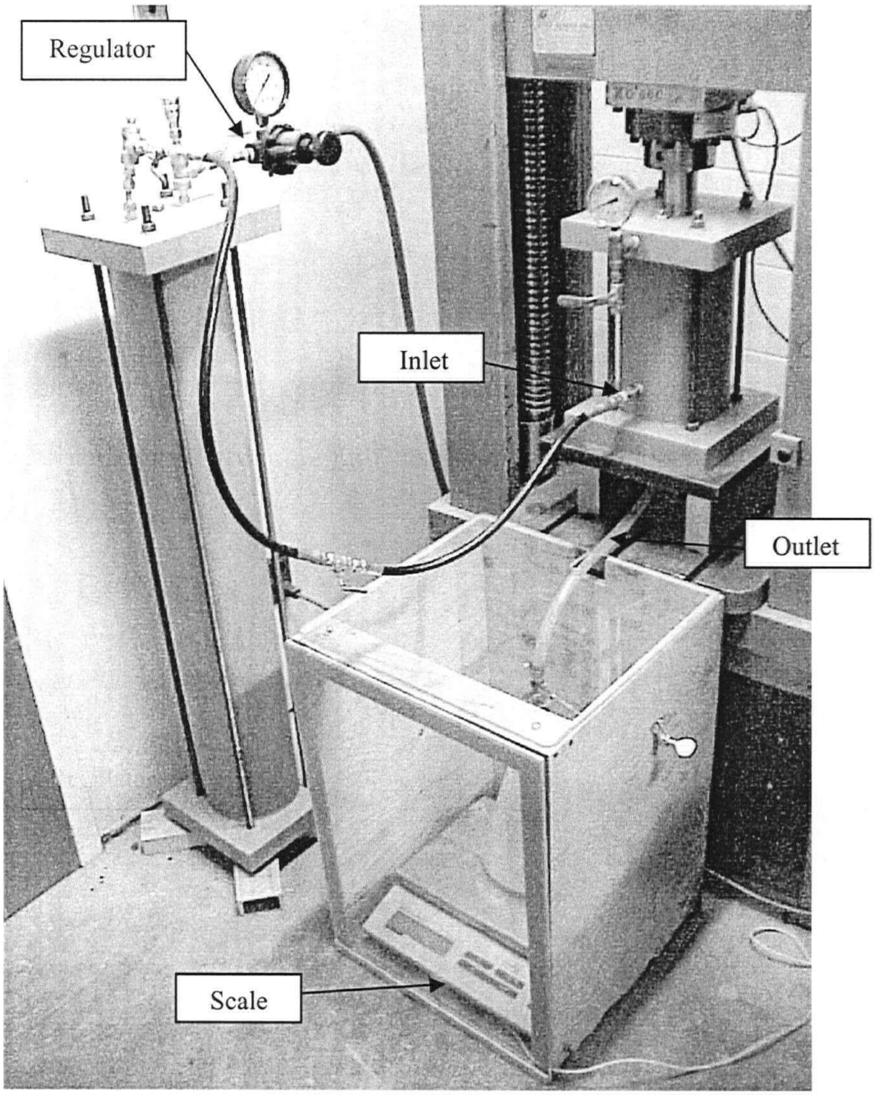


Figure 4.8. **Test Setup Showing the Feed Water Tank and the Outlet**

Figure 4.9. **Compression Testing Machine**

Permeability Tests- Four series of tests as shown in Table 4.3 were performed. In each series, two specimens were tested: one under no stress and the other with stress. In Series 1, the stressed specimen carried a stress equal to $0.2f_u$ applied at the age of 1 day, where f_u the ultimate strength in compression is 10.5 MPa. In Series 2, the stressed specimen carried a stress equal to $0.4f_u$ applied again at the age of 1 day.

In Series 3, the stressed specimen carried a stress equal to $0.3f_u$ applied at the age of 3 days. Finally, in Series 4, specimens tested in Series 2 were tested again while the stress level was increased to $0.3f_u$. The stress on the specimen was kept constant during the test and any stress relaxation in the machine was properly accounted for by further moving the loading arm. The actual values of the applied stress in each series are also reported in Table 4.3.

The hydraulic pressure was applied to the outside wall of the hollow cylinder. The driving pressure was controlled by a regulator and kept constant throughout the test and a calibrated pressure gauge was used to indicate the inflow pressure. Extreme caution was exercised to detect any leakage in the system.

The permeated water was collected from the hollow core into a reservoir and its weight was measured accurately as a function of time using a computer controlled scale (Figure 4.8).

Table 4.3. **Test Details (Set1)**

Series	1		2		3		4*	
Specimen Age	1day		1day		3 days		3 days	
Compressive Strength, f_u	10.5 MPa		10.5 MPa		26.0 MPa		26.0 MPa	
Driving Pressure	50 PSI		50 PSI		50 PSI		50 PSI	
Specimen Designation**	S1-0	S1-L	S2-0	S2-L	S3-0	S3-L	S4-0	S4-L
Applied Stress	None	$0.2 f_u$ (2.1 MPa)	None	$0.4 f_u$ (4.2 MPa)	None	$0.3 f_u$ (7.8 MPa)	None	$0.3 f_u$ (7.8 MPa)

** Continuation from Series 2 where three days after casting, the load on the specimen S2-L was increased to $0.3f_u$ (7.8 MPa). Note that specimens S3-L and S4-L had the same applied stress except that Specimen SL-4 was previously loaded to $0.4f_u$ in Series 2 tests.*

*** Designation S n-0 : Specimen in series n while no stress is applied*

S n-L: Specimen in series n while stressed to a specific level

Under steady-state conditions, the coefficient of permeability (K_w) at different age of the specimen can be obtained based on Darcy's law using the following equation:

$$K_w = Q.L / A.\Delta h$$ **Equation 4.1**

where

K_w = Coefficient of water permeability (m/s)

Q = Rate of Water Flow (m^3/s)

L = Thickness of specimen wall (m)

A = Permeation area (m^2)

Δh = Pressure head (m)

4.2 PERMEABILITY OF HIGH VOLUME FLY ASH CONCRETE

The second part of this research involved investigation of fly ash effects on the early age permeability of concrete. Fly ash as a cement replacement was added into the concrete mix and the permeability was measured using the UBC permeability cells. In this part, the samples were tested in an unstressed condition and only the fly ash content was varied.

4.2.1 CONCRETE MIXTURES

The mix proportions of concrete used in the test program are given in Table 4.4. CSA Type 10 normal Portland cement (ASTM Type I), coarse aggregate with a maximum size of 9.5 mm, saturated surface-dry (SSD) clean river sand with a fineness modulus of about 2.5, Type CI fly ash, and potable water were used. The physical and chemical properties of fly ash are given in Table 4.5.

Table 4.4. **Concrete Mix Proportions (Set 2)**

Series	1	2	3
Ingredient	**Plain Concrete**	**25% Fly Ash**	**50% Fly Ash**
Cement (kg/m³)	400	300	200
w/c Ratio	0.4	0.4	0.4
Water (kg/m³)	160	160	160
Aggregate (kg/m³)	850	850	850
Sand (kg/m³)	850	850	850
Fly Ash (kg/m³)	0	100	200

Table. 4.5. **Chemical and Physical Properties of Fly Ash [56]**

FLY ASH TYPE CI **Plant of Origin: Centralia US**	
Chemical Composition(%)	
ASTM 618-03 Specification	
Total Silica, Aluminium, Iron:	50.0 Min
Silicon Dioxide:	51.1
Aluminium Oxide:	23.8
Iron Oxide:	5.9
Sulfur Trioxide:	5.0 Max
Calcium Oxide:	8.8
Moisture Content:	3.0 Max
Loss of Ignition:	6.0 Max
Physical Test Results	
ASTM 618-03 Specification	
Fineness, Retained on #325 Sieve(%):	34 Max
Strenght Activity Index (%)	
Ratio to Control @ 7 Days:	80.4
Ratio to Control @ 28 Days:	90.7 (75 Min)
Wather Requirement, % of Control:	92.1 (105 Max)
Soundness, Autoclave Expansion (%):	0.8 Max
Dry Shirinkage, increase @ 28 Days (%):	0.3 Max
Density:	2.25

4.2.2 TEST METHODS

The same procedure was followed for preparing, sealing, and assembling the cells tested in the second phase of this study. As mentioned earlier, in this set of tests the fly ash content was the only variable. A total of three series of tests with different fly ash contents (0%, 25%, and 50%) were tested (see Table 4.6). An overview of the experimental work is given in Figure 4.10.

Table 4.6. **Test Details (Set2)**

Series	1		2		3	
Specimen Age	1day		1day		1 day	
Driving Pressure	0.21 MPa		0.21 MPa		0.21 MPa	
Specimen Designation*	S1-P	S1-F	S2-P	S2-F	S3-F	S3-F
Fly Ash %	None	25	None	50	25	50

* Designation: P for plain and F for fly ash concrete.

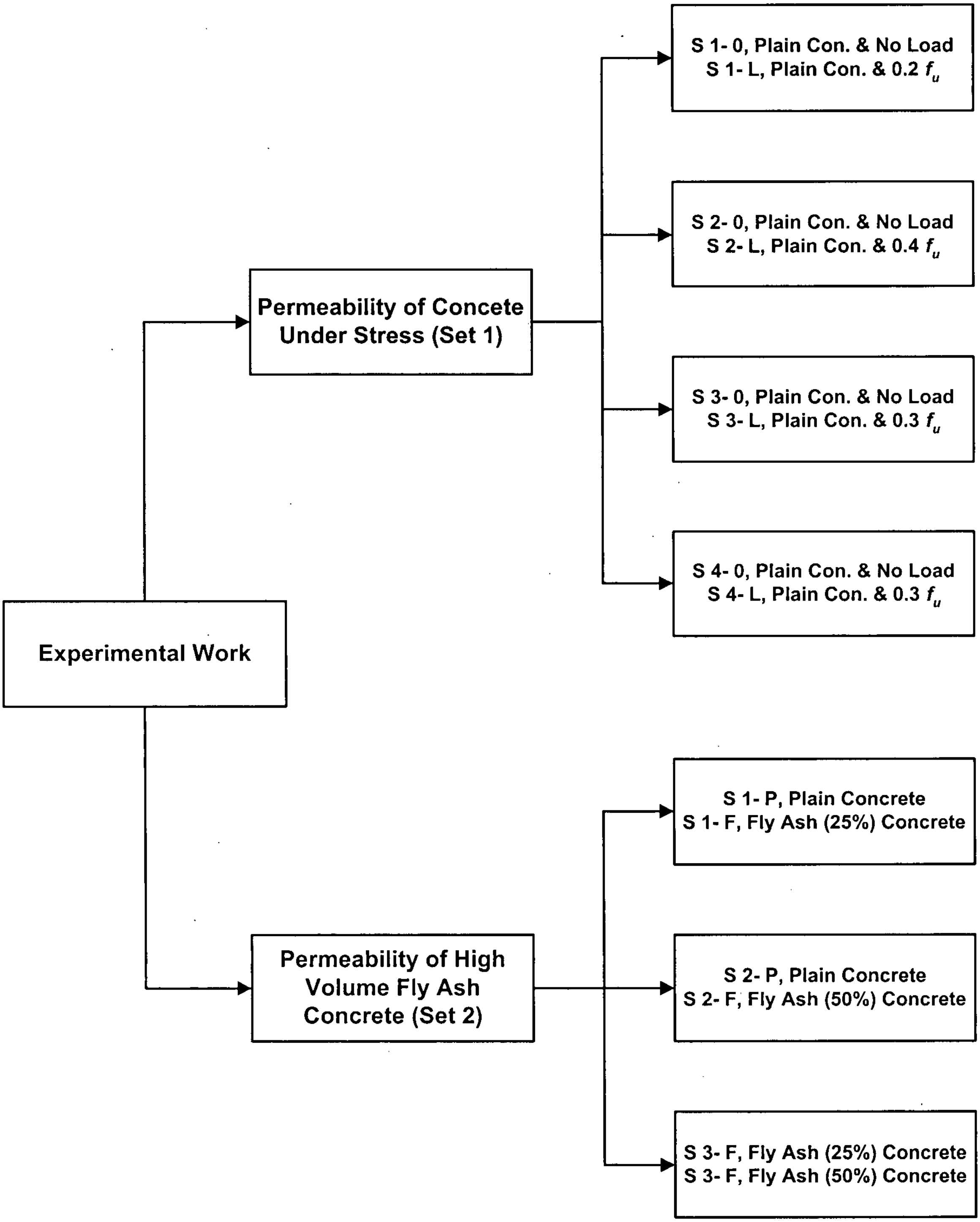


Figure 4.10. **Experimental Program**

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, results of this experimental study are presented and analyzed. In order to assess the effects of stress on permeability of early age concrete, the experimental results for stressed and unstressed samples are compared. In the second part, the effects of fly ash on compressive strength and permeability of early age concrete are presented and discussed.

5.1 PERMEABILITY OF CONCRETE UNDER STRESS

Three cylindrical specimens were tested in compression for each series. The compressive strengths (f_u), their average values, standard deviations, and coefficients of variation are given in Table 5.1. Standard deviations of the results were from 0.49 to 0.69 MPa and coefficients of variation were from 2 to 6.5 %. Twenty percent of average compressive strength (2.1 MPa) in series 1, 40% of average compressive strength (4.2

MPa) in series 2, and 30% of average compressive strength (7.8 MPa) in series 3 and 4 were applied on the specimens as appropriate.

Table 5.1 **Compressive Strengths (Set 1)**

Series	**1**	**2**	**3**	**4**
Age (Day)	1	1	3	3
Compressive	10.40	9.70	26.70	25.30
Strength	9.90	11.40	25.40	26.70
(MPa)	11.10	10.50	26.00	25.80
Average	**10.46**	**10.53**	**26.03**	**25.93**
Standard Deviation (MPa)	0.49	0.69	0.53	0.58
Coefficient of Variation %	4.70	6.50	2.00	2.30

The permeability coefficient was determined from the measurements of sample geometry, steady state flow through the sample, and the applied pressure. The measured flow volumes within the inner core of the specimen underestimated the permeability coefficients. In any case, the calculated values represent actual flow through the specimen and hence are true representations of the concrete's ability to allow permeation through it. The permeability coefficients of concrete are given in Tables 5.2 to 5.5 and displayed in Figures 5.1 to 5.4. In Figures 5.1 to 5.4, permeability values are plotted as a function of time for the four series of tests. For every series, the coefficient of permeability fluctuated during the test. A number of factors such as variation in temperature, humidity, accuracy of the measurement system, and osmotic pressure may be responsible for this variation. The best-fit linear trend lines were drawn through the permeability curves and these are also shown in Figures 5.1 to 5.4.

Table 5.2 **Series 1 (1 day @ $0.2f_u$)**

Time (Hours)	Permeability (m/s) With load	Permeability (m/s) Without load
1	3.72×10^{-10}	1.97×10^{-10}
2	3.72×10^{-10}	1.92×10^{-10}
3	3.7×10^{-10}	1.82×10^{-10}
4	3.7×10^{-10}	1.75×10^{-10}
5	3.66×10^{-10}	1.63×10^{-10}
6	3.64×10^{-10}	1.6×10^{-10}
7	3.6×10^{-10}	1.59×10^{-10}
8	3.6×10^{-10}	1.41×10^{-10}
9	3.59×10^{-10}	1.4×10^{-10}
10	3.57×10^{-10}	1.43×10^{-10}
11	3.54×10^{-10}	1.31×10^{-10}
12	3.53×10^{-10}	1.37×10^{-10}
13	3.5×10^{-10}	1.33×10^{-10}
14	3.48×10^{-10}	1.29×10^{-10}
15	3.46×10^{-10}	1.31×10^{-10}
16	3.44×10^{-10}	1.31×10^{-10}

Table 5.3 **Series 2 (1 day @ $0.4f_u$)**

Time (Hours)	Permeability (m/s) With load	Permeability (m/s) Without load
1	1.72×10^{-10}	1.81×10^{-10}
2	1.63×10^{-10}	1.74×10^{-10}
3	1.57×10^{-10}	1.71×10^{-10}
4	1.54×10^{-10}	1.68×10^{-10}
5	1.54×10^{-10}	1.66×10^{-10}
6	1.53×10^{-10}	1.65×10^{-10}
7	1.49×10^{-10}	1.61×10^{-10}
8	1.45×10^{-10}	1.60×10^{-10}
9	1.40×10^{-10}	1.59×10^{-10}
10	1.36×10^{-10}	1.51×10^{-10}
11	1.30×10^{-10}	1.50×10^{-10}
12	1.24×10^{-10}	1.49×10^{-10}
13	1.21×10^{-10}	1.37×10^{-10}
14	1.20×10^{-10}	1.37×10^{-10}
15	1.20×10^{-10}	1.44×10^{-10}
16	1.15×10^{-10}	1.40×10^{-10}

Table 5.4 **Series 3 (3 day @ 0.3f_u)**

Time (Hours)	Permeability (m/s) With load	Permeability (m/s) Without load
1	2.91×10^{-10}	1.22×10^{-10}
2	2.95×10^{-10}	1.40×10^{-10}
3	2.88×10^{-10}	1.20×10^{-10}
4	2.98×10^{-10}	1.28×10^{-10}
5	2.87×10^{-10}	1.17×10^{-10}
6	2.85×10^{-10}	1.16×10^{-10}
7	2.90×10^{-10}	1.20×10^{-10}
8	2.83×10^{-10}	1.15×10^{-10}
9	2.83×10^{-10}	1.15×10^{-10}
10	2.81×10^{-10}	1.14×10^{-10}
11	2.90×10^{-10}	1.13×10^{-10}
12	2.68×10^{-10}	1.01×10^{-10}
13	2.78×10^{-10}	1.11×10^{-10}
14	2.77×10^{-10}	1.09×10^{-10}
15	2.63×10^{-10}	1.09×10^{-10}
16	2.61×10^{-10}	1.09×10^{-10}

Table 5.5 **Series 4 (3 day @ 0.3f_u)**

Time (Hours)	Permeability (m/s) With load	Permeability (m/s) Without load
1	6.1×10^{-9}	1.14×10^{-10}
2	5.7×10^{-9}	1.11×10^{-10}
3	5.2×10^{-9}	1.09×10^{-10}
4	5.0×10^{-9}	1.04×10^{-10}
5	5.9×10^{-9}	1.06×10^{-10}
6	5.7×10^{-9}	9.7×10^{-9}
7	5.6×10^{-9}	9.4×10^{-9}
8	6.2×10^{-9}	1.02×10^{-10}
9	6.3×10^{-9}	9.2×10^{-9}
10	5.9×10^{-9}	1.06×10^{-10}
11	6.2×10^{-9}	8.3×10^{-9}
12	6.1×10^{-9}	8.0×10^{-9}
13	5.3×10^{-9}	7.5×10^{-9}
14	5.3×10^{-9}	8.2×10^{-9}
15	5.2×10^{-9}	7.8×10^{-9}
16	5.0×10^{-9}	7.7×10^{-9}

Experimental results of permeability tests (Table 5.2 to 5.5) showed the diminution in permeability with the progress of hydration. At an early age, the pore system is evolving, and the stability of the pore system increases with time. As the hydration of cement grains takes place, hydration products fill the voids and the speed of water flow is reduced. Hence, decrease in permeability due to hydration in fresh concrete is much faster than that in mature concrete.

During hydration, the capillaries are being segmented. This segmentation inside the pore structure of concrete increases the tortuosity of the continuous pores and reduces the size of pores. Clearly the initial w/c ratio of the mix has a significant effect on the apparent rate of segmentation of capillary pores and drop in permeability. Powers [58] stated that an increase in w/c ratio leads to an increase in the time taken for capillaries to segment (see Table 5.6).

Table 5.6. **Capillary Segmentation Time at Various w/c**

w/c ratio	Time
0.4	3 days
0.45	7 days
0.5	14 days
0.6	6 months
0.7	1 year
> 0.7	Impossible

As illustrated in Table 5.6, at a w/c of 0.6 the segmentation takes place after 6 months. Therefore in this study with a w/c = 0.6, after 3 days segmentation may not have occurred. Notice that a decrease in the coefficient of permeability occurred with time, which was expected due to continued hydration in the specimen as well as potential pore-blocking [57].

Other than hydration, clogging or pore blocking can be another possible cause of decreasing permeability. As stated by Kermani [35], clogging is due to very fine particles carried from one part of the concrete and deposited in the pores in another part. At high hydraulic pressure clogging plays the major part in reducing the permeability, but in this investigation clogging may not have played a major role on the permeability reduction. Firstly, the applied hydraulic pressure was low; secondly at early ages the canals and pores are wide and large that will not allow clogging. The slope of permeability versus time curve is the rate of change in permeability with respect to time. Based on the experimental results, stress had no effect on the rate of permeability changes and the slopes remained almost the same in series 1,2, and 4.

Unlike capillary pores, the size of gel pores is independent of the w/c ratio and time of hydration for normally cured cement paste; the overall volume of gel pores is about 28% of the total volume of pores in the hydration component of normally cured concrete. Hence, the effects of gel pores on stressed concrete are negligible [59].

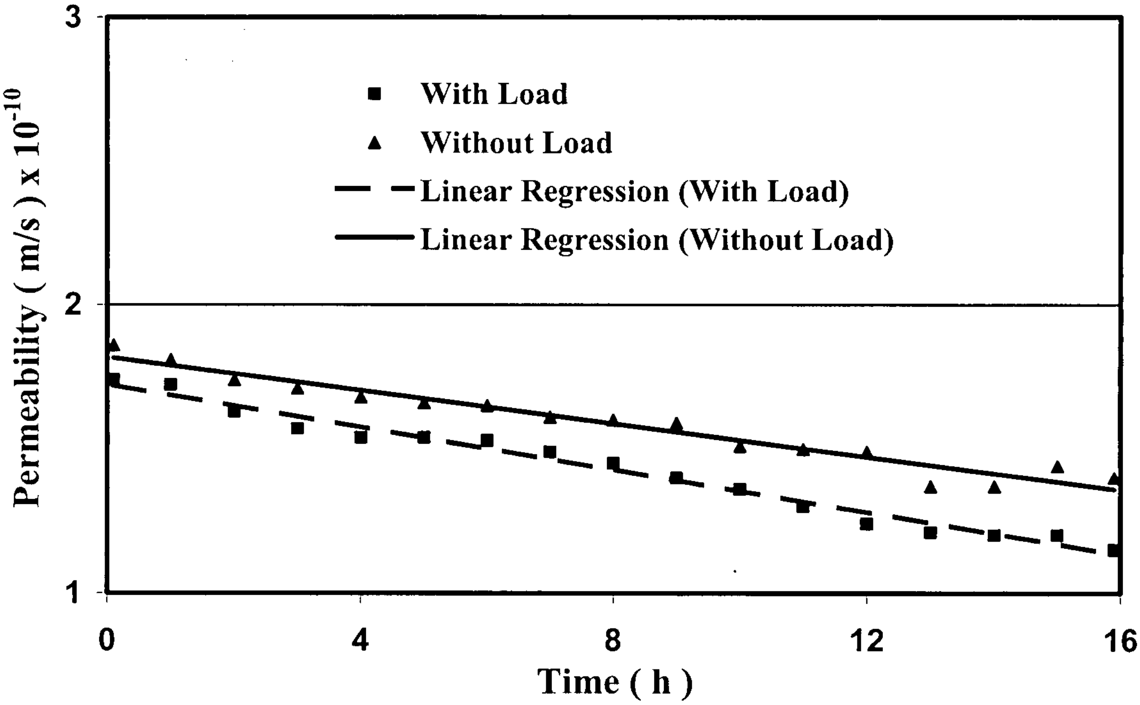


Figure 5.1. **Permeability Plots for Stressed (1 day @ 0.2f_u) and Unstressed Specimen (Series 1)**

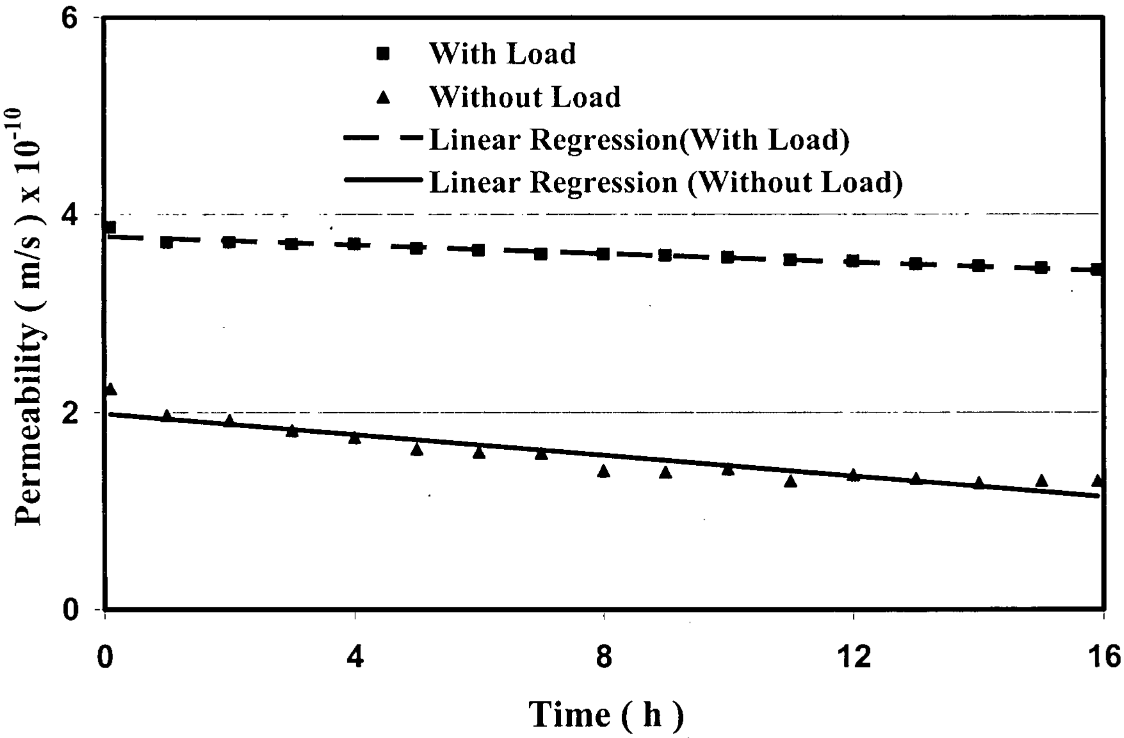


Figure 5.2. **Permeability Plots for Stressed (1 day @ 0.4f_u) and Unstressed Specimen (Series 2)**

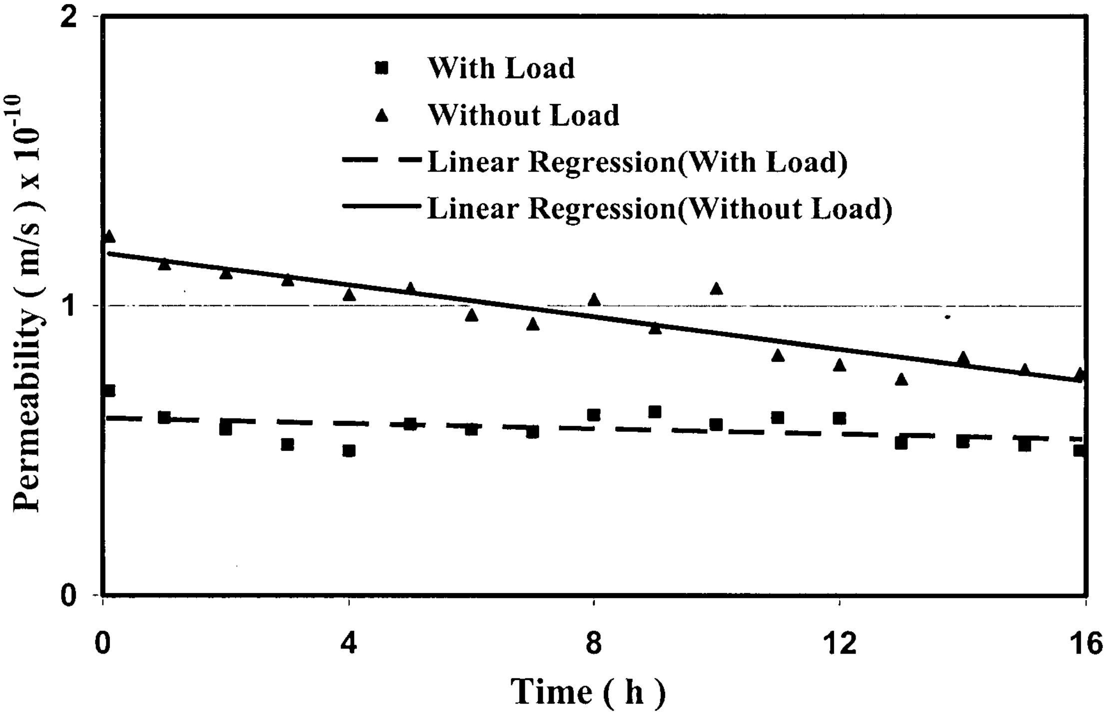


Figure 5.3. **Permeability Plots for Stressed (3 day @ 0.3f_u) and Unstressed Specimen (Series 3)**

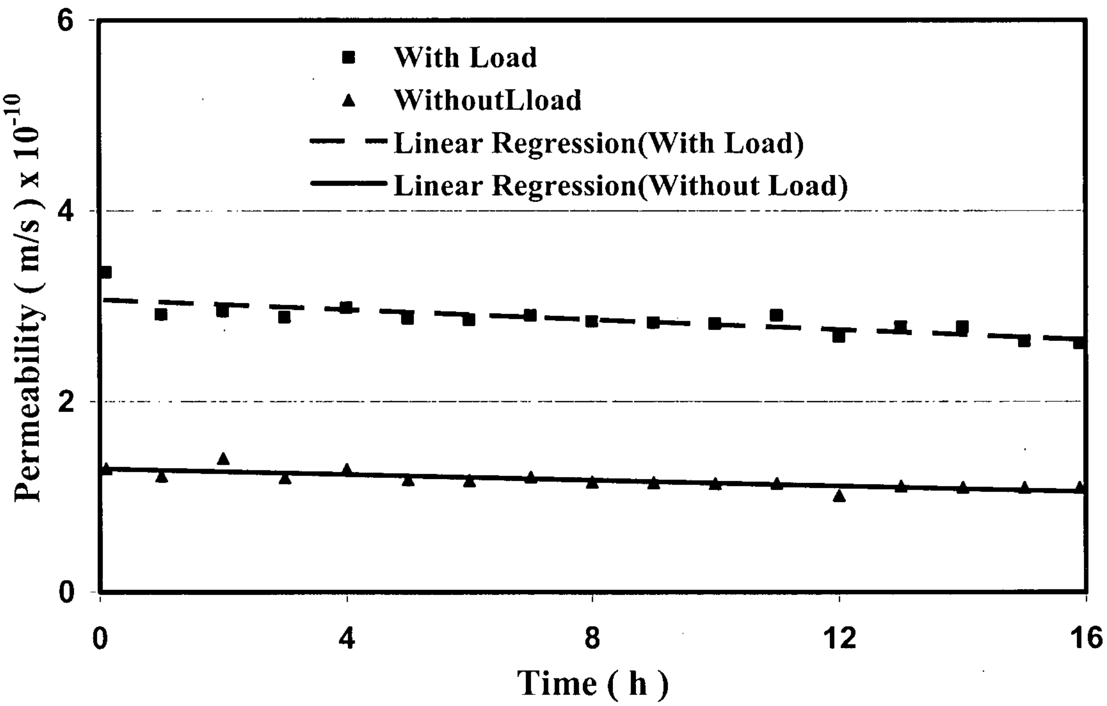


Figure 5.4. **Permeability Plots for Stressed (3 day @ 0.3f_u) and Unstressed Specimen (Series 4)**

Tests from Series 1 indicated that at an applied stress of $0.2f_u$, there was a small decrease (10%) in the measured coefficient of permeability verses the unstressed specimen. At a stress of $0.4f_u$, on the other hand, a significant increase (130%) in the permeability was observed (Figure 5.5).

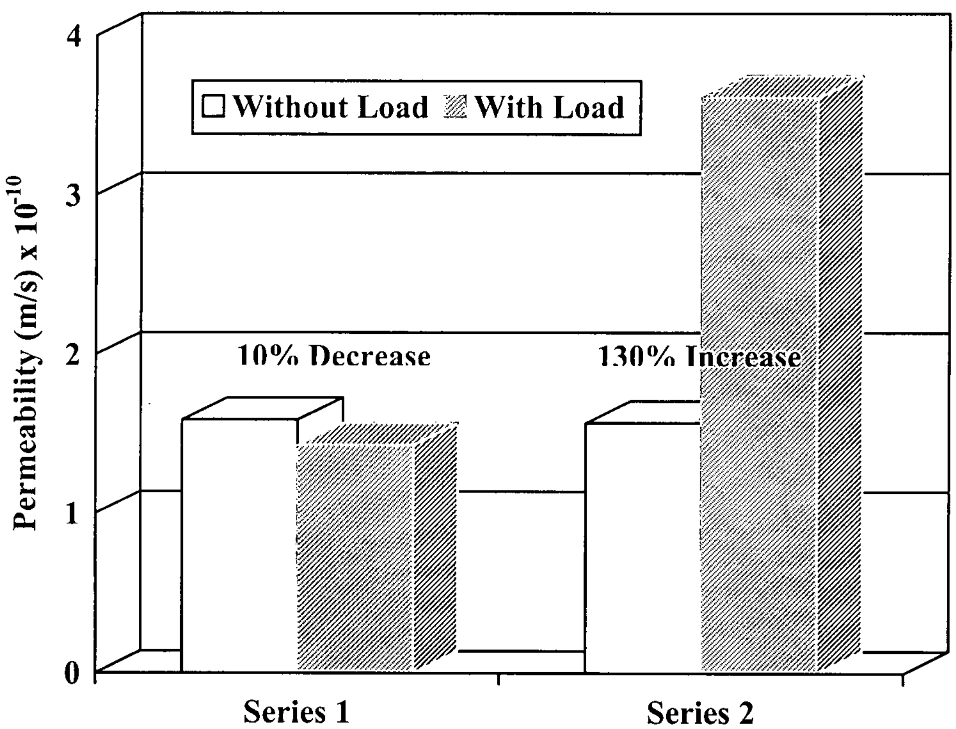


Figure 5.5. **Effects of Stress on Concrete Permeability for 1day old samples**

In Figure 5.3, a stress of $0.3f_u$ applied at an age of 3 days can, once again, be seen to decrease the permeability. However, when the same level of stress ($0.3 f_u$) is applied to a specimen, which had already suffered irreversible damage at the age of 1 day (Figure 5.4, Series 4), one can see that a significant increase (140% increase) in permeability occurred. Thus, it appears that a premature loading can create irreversible damage in the specimen, which will adversely affect later age permeability even under low stress application. Loading history therefore appears to be a critical factor controlling permeation through concrete.

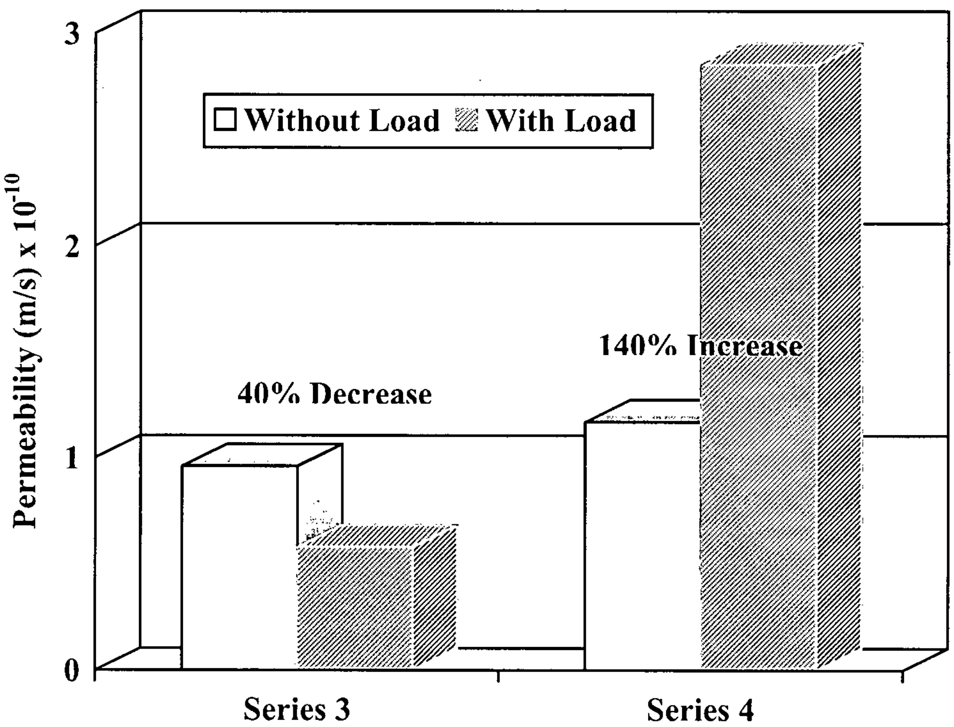


Figure 5.6. **Effects of Stress on Concrete Permeability for 3day old samples**

This is predictable as the stress-strain curve for concrete is expected to be linear up to about $0.3f_u$ and noticeably non-linear with irreversible damage and micro cracking thereafter. These findings are supported by the results of Kermani [35], who found that permeability increased significantly when the stress level exceeded 40% of the ultimate strength. Reda and Shrive [60] purposed that, the non-linear behavior of concrete under stress could be explained by defining concrete as a three phase heterogeneous material; the cement paste, the aggregate and the transition zone (TZ). Because of its high porosity and low strength, micro cracks can easily propagate in the transition zone while the other two phases are not cracked. This results in a nonlinear behavior of concrete. Cui [61] and Kotsovos [62] have presented similar theories.

It was found that the presence of a compressive stress below a certain threshold value decreased the permeability, but when the applied stress exceeded this threshold, a significant increase in the permeability occurred (Figure 5.7).

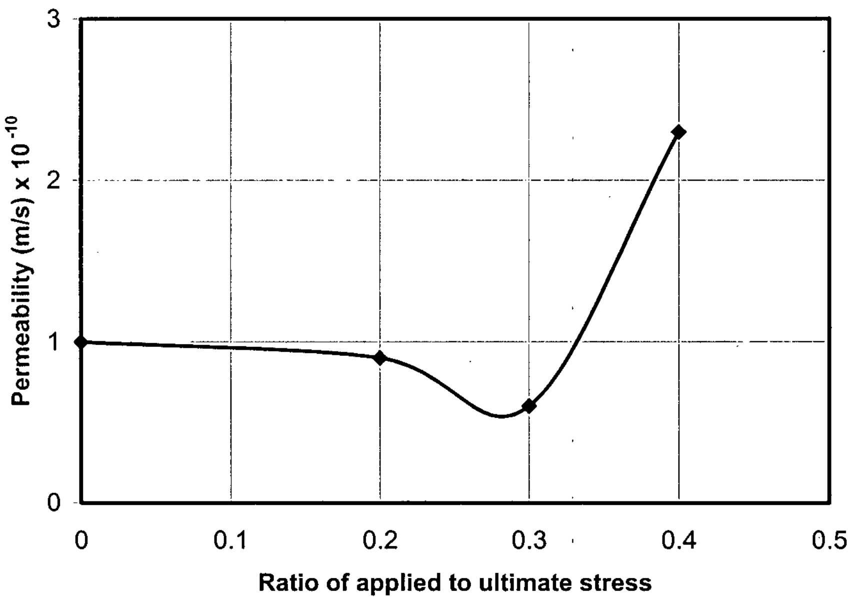


Figure 5.7. **Effect of applied stress on water permeability**

The changes in the permeability of concrete due to stress can be explained by the fracture behavior of concrete (Figure 5.8). Voids and cracks can be simplified as vertical and horizontal cracks.

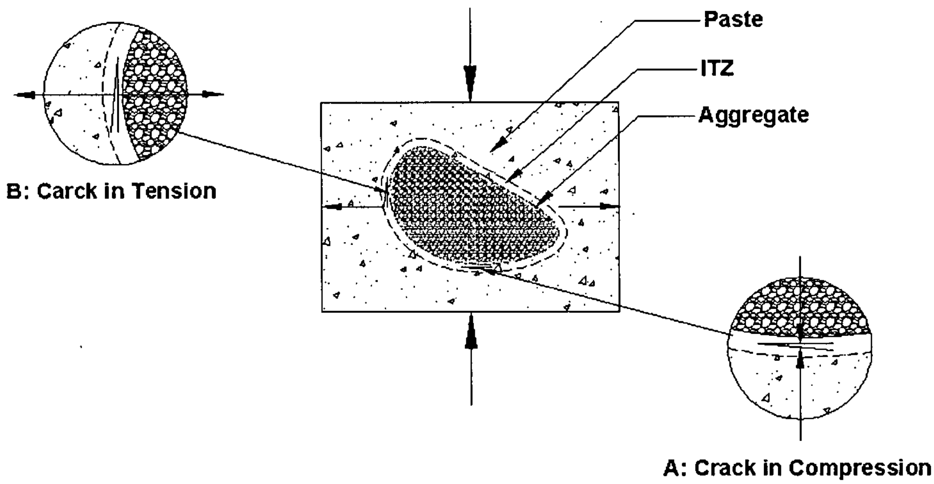


Figure 5.8. **Crack types A: Crack in compression B: Crack in tension**

Under a compressive stress of 0.3 f_u the vertical cracks likely remain stable and the horizontal cracks are closed. At this level of compressive stress the tensile stress is apparently less than the cohesive strength of the material and the system remains stable.

As the stress is increased beyond 0.3 f_u the cracks start growing in length, width and number [63]. The micro cracks in the loaded specimens are generated by different mechanisms. Micro cracks appear at the interfacial transition zone, through the aggregate and at the voids. In mature concrete, the weakest link is located at the transition zone and in early age concrete they are located at the voids.

In order to assess the reliability of results two identical specimens were tested at 1 day (Table 5.7) and at 3 days (Table 5.8) unstressed state and the results were compared. The results are plotted in Figures 5.9 and 5.10. Notice that for one-day specimens, the standard deviation of the results was from 2 x 10^{-8} to 3 x 10^{-9} m/s and the coefficient of variation was from 1.4 to 14.6 %. The standard deviation of 3 day old samples varied from 4 x 10^{-8} to 1.8 x 10^{-9} m/s and the coefficient of variation was from 2.1 to 19.5 %. Theses are generally low values given the large variation generally observed in permeability test.

Table 5.7. **Permeability of 1-day old samples**

Series 1 K_W (m/s) x 10^{-10}	Series 2 K_W (m/s) x 10^{-10}	Standard deviation (m/s) x 10^{-10}	Coefficient of variation (%)
1.86	2.24	0.30	14.65
1.81	1.97	0.13	6.69
1.74	1.92	0.14	7.78
1.71	1.82	0.09	4.93
1.68	1.75	0.06	3.23
1.66	1.63	0.02	1.44
1.65	1.6	0.04	2.43
1.61	1.59	0.02	0.99
1.6	1.41	0.15	9.98
1.59	1.4	0.15	10.05
1.51	1.43	0.06	4.30
1.5	1.31	0.15	10.69
1.49	1.37	0.09	6.63
1.37	1.33	0.03	2.34
1.37	1.29	0.06	4.76
1.44	1.31	0.10	7.47
1.4	1.31	0.07	5.25

Table 5.8. **Permeability of 3-day old samples**

Series 3 K_W (m/s) x 10^{-10}	Series 4 K_W (m/s) x 10^{-10}	Standard deviation (m/s) x 10^{-10}	Coefficient of variation (%)
1.24	1.29	0.03	2.08
1.14	1.22	0.04	3.05
1.11	1.40	0.14	11.37
1.09	1.20	0.05	4.74
1.04	1.29	0.12	10.64
1.06	1.18	0.06	5.31
0.97	1.17	0.10	9.39
0.94	1.20	0.13	12.44
1.02	1.15	0.07	6.01
0.92	1.15	0.11	10.76
1.06	1.14	0.04	3.46
0.83	1.14	0.15	15.61
0.80	1.01	0.11	11.87
0.75	1.11	0.18	19.49
0.82	1.10	0.14	14.14
0.78	1.10	0.16	16.83
0.77	1.10	0.16	17.63

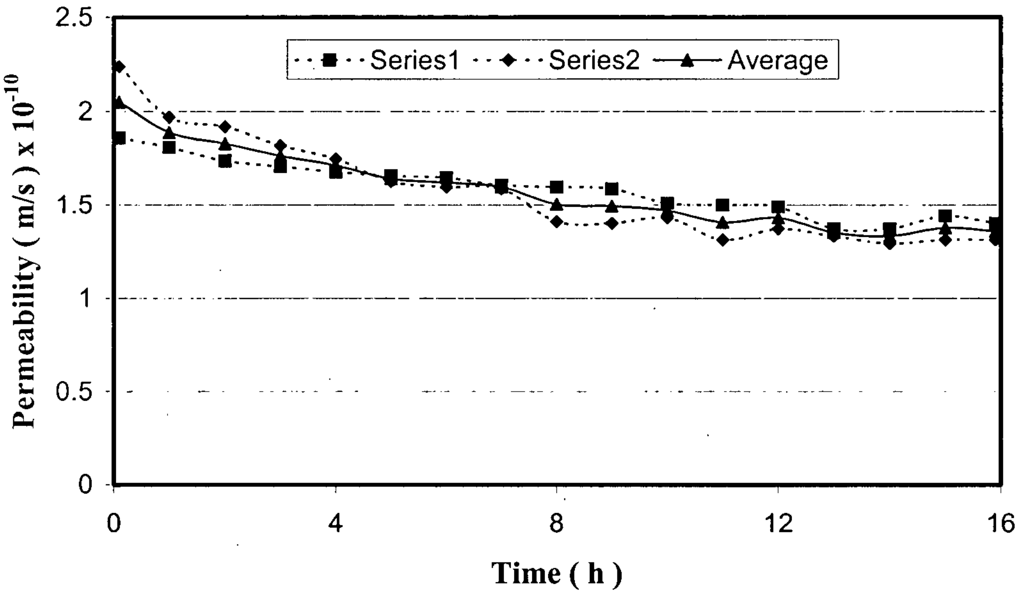


Figure 5.9. **Standard deviation of 1-day old samples**

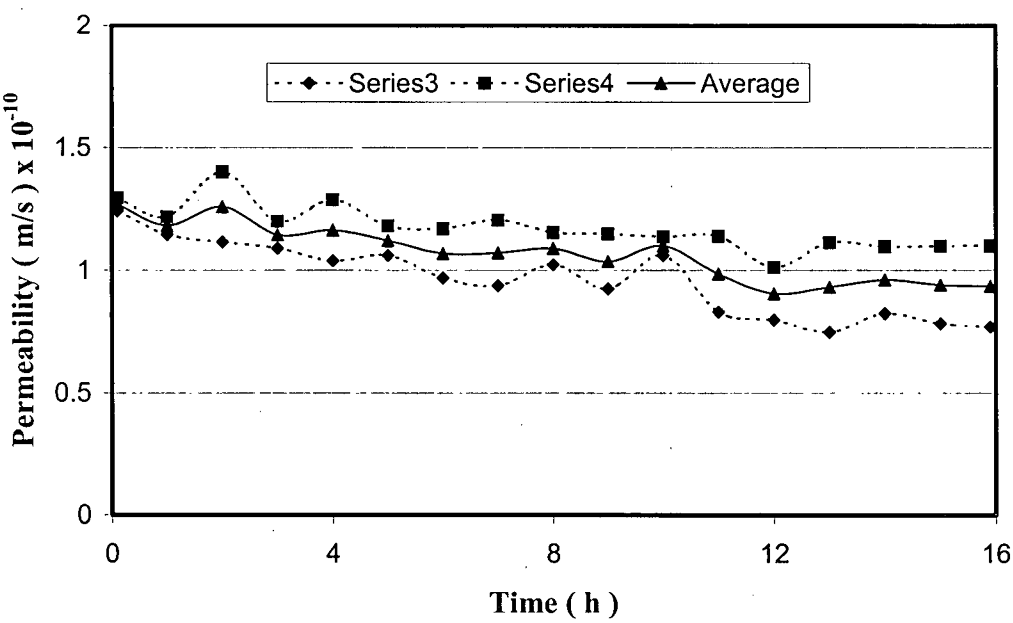


Figure 5.10. **Standard deviation of 3-day old samples**

5.2 HIGH VOLUME FLY ASH CONCRETE

Compressive strength: The results of compression test of three mixes with different fly ash replacement rates are shown in Table 5.9. The standard deviation of the results was from 0.39 to 4 MPa and coefficient of variation was from 0.6 to 5.5 %.

Table 5.9 **Compressive strength results of high volume fly ash concrete**

		1 day (MPa)	7 day (MPa)	28 day (MPa)	56 day (MPa)
	# 1	32.29	62.41	75.36	77.44
Mix 1(Plain Concrete)	# 2	32.71	62.21	73.85	71.79
	# 3	36.44	63.14	66.13	81.94
	Average(MPa)	33.81	62.59	71.78	77.06
	Standard Deviation (MPa)	1.86	0.39	4.00	4.15
	Coefficient of Variation %	5.50	0.60	5.60	5.39
	# 1	24.16	51.04	63.95	75.34
Mix 2(25% Fly Ash)	# 2	24.04	50.39	62.76	77.78
	# 3	22.06	49.05	59.84	75.53
	Average(MPa)	23.42	50.16	62.18	76.22
	Standard Deviation (MPa)	0.96	0.82	1.70	1.10
	Coefficient of Variation %	4.00	1.60	2.70	1.45
	# 1	11.93	28.49	39.63	50.61
Mix 3(50% Fly Ash)	# 2	10.84	28.29	35.15	49.89
	# 3	11.28	29.58	35.99	49.33
	Average(MPa)	11.35	28.79	36.92	49.94
	Standard Deviation (MPa)	0.45	0.57	1.94	0.52
	Coefficient of Variation %	3.95	1.97	5.30	1.00

Figure 5.11 plotted the compressive strength versus age of different mixes with 0%, 25%, and 50% replacement of fly ash. The average value of three samples of each mix was used for comparison.

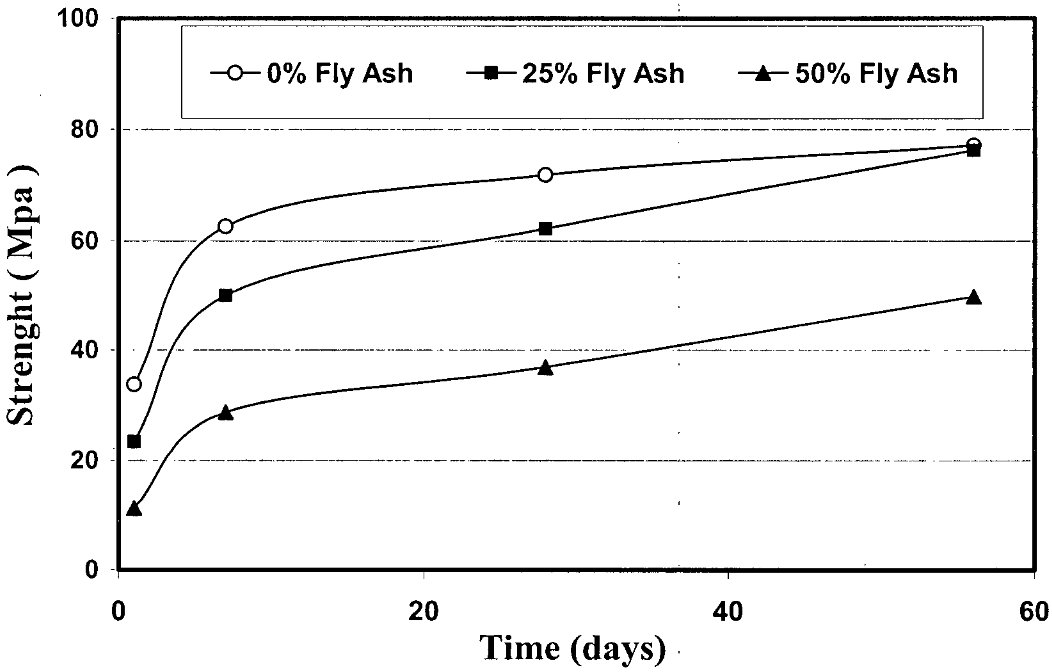


Figure 5.11. **Compressive strength of concrete with different fly ash content**

The compressive strength test results showed that the concrete made with 0%, 25%, and 50% fly ash developed 7-day compressive strength of 62, 50 and 28 MPa, respectively. With higher percentage of cement replacement the compressive strength decreased due to reduced cement contents and delayed pozzolanic reaction of fly ash. Beyond 7 days, the HVFA concrete due to pozzolanic reactions started developing compressive strength at a higher rate than that of the control concrete, and at 56 days, the compressive strength of 25% fly ash concrete (76.22 MPa) approached that of the control concrete (77.06 MPa). In general, in spite of the low strength measured in early ages, the HVFA concrete caught up with the control concrete. This is especially significant bearing in mind the low cement content of the mixture [64].

Permeability of high volume fly ash concrete: In Table 5.10, the coefficients of permeability calculated using Darcy's equation are shown for mixes with 0%, 25%, and 50% fly ash replacement rates at one day age. The results showed no improvement in water permeability of concrete with fly ash replacement, and no significant trend was observed between mixes with different fly ash contents at early age.

Table 5.10. **Permeability of HVFA concrete @ 1 day age**

Time (hours)	Permeability (m/s) 0% Fly Ash	Permeability (m/s) 25% Fly Ash	Permeability (m/s) 50% Fly Ash
1	0.56×10^{-10}	1.97×10^{-10}	3.54×10^{-10}
2	0.54×10^{-10}	1.91×10^{-10}	3.33×10^{-10}
3	0.53×10^{-10}	1.82×10^{-10}	3.17×10^{-10}
4	0.50×10^{-10}	1.77×10^{-10}	2.93×10^{-10}
5	0.45×10^{-10}	1.73×10^{-10}	2.66×10^{-10}
6	0.41×10^{-10}	1.64×10^{-10}	2.48×10^{-10}
7	0.45×10^{-10}	1.58×10^{-10}	2.43×10^{-10}
8	0.38×10^{-10}	1.53×10^{-10}	2.28×10^{-10}
9	0.36×10^{-10}	1.46×10^{-10}	2.22×10^{-10}
10	0.33×10^{-10}	1.41×10^{-10}	2.04×10^{-10}
11	0.30×10^{-10}	1.37×10^{-10}	1.86×10^{-10}
12	0.30×10^{-10}	1.32×10^{-10}	1.69×10^{-10}
13	0.27×10^{-10}	1.26×10^{-10}	1.65×10^{-10}
14	0.29×10^{-10}	1.22×10^{-10}	1.64×10^{-10}
15	0.25×10^{-10}	1.19×10^{-10}	1.49×10^{-10}
16	0.24×10^{-10}	1.16×10^{-10}	1.38×10^{-10}
17	0.26×10^{-10}	1.14×10^{-10}	1.43×10^{-10}
18	0.24×10^{-10}	1.11×10^{-10}	1.35×10^{-10}
19	0.21×10^{-10}	1.08×10^{-10}	1.40×10^{-10}
20	0.21×10^{-10}	1.04×10^{-10}	1.20×10^{-10}
21	0.17×10^{-10}	1.01×10^{-10}	1.28×10^{-10}
22	0.15×10^{-10}	0.96×10^{-10}	1.07×10^{-10}
23	0.14×10^{-10}	0.95×10^{-10}	0.98×10^{-10}
24	0.08×10^{-10}	0.91×10^{-10}	0.90×10^{-10}

The comparison of the decreasing permeability coefficient among different fly ash replacement specimens is plotted as a function of time for the three series of tests in Figure 5.12. The slope of the permeability versus time curve is the rate of change in permeability with respect to time. In this study, the rate of change of permeability of different mixes was influenced by fly ash percentage replacement. Experimental results showed that the higher the fly ash content in the mix, the grater the rate of permeability change in the concrete.

When fly ash is used as a supplementary cementing material, due to the set retarding effect and lower rates of pozzolanic reaction of fly ash, specimens require more time to achieve discontinuity in pore structure than the control ordinary Portland cement samples. The time lag is also higher for higher fly ash content mixes [65].

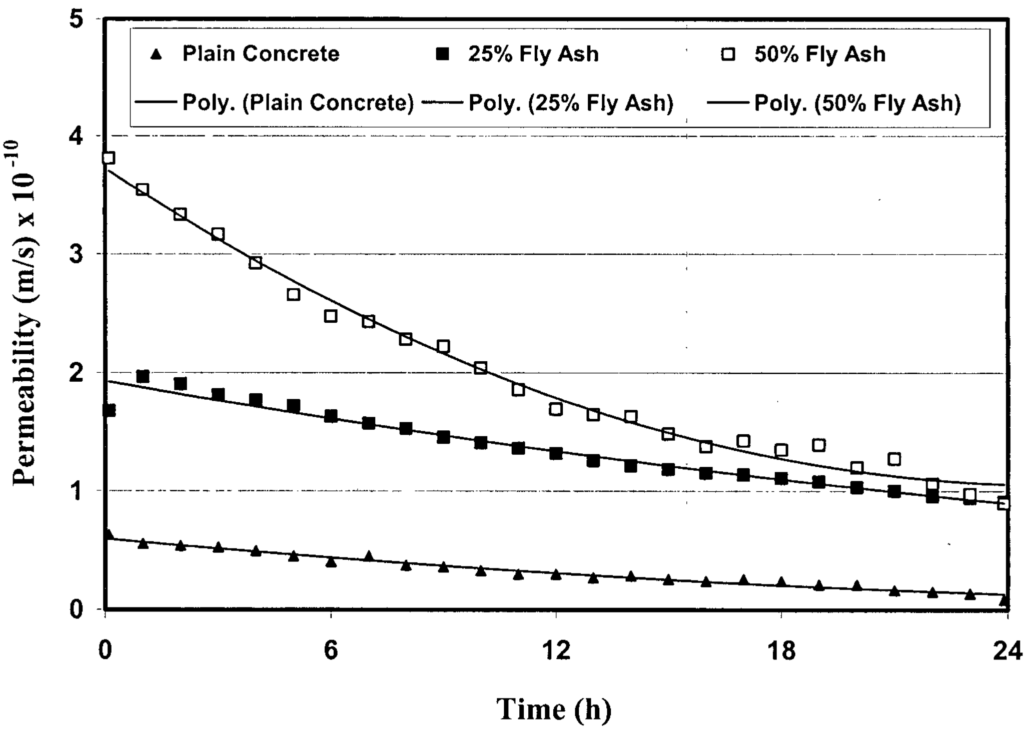


Figure 5.12. **Permeability of High Volume Fly Ash Concrete**

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

In this chapter, the principal observation and conclusions drawn from this study are summarized. The primary objective of this study was to develop a test method capable of measuring the water permeability of concrete when it is under an applied stress, to investigate the influence of stress application on the permeability of concrete at an early age (1-3 days), and the effects of fly ash on the early age permeability of concrete.

For this purpose, two permeability cells were built at the University of British Columbia. One cell was mounted in a Universal Testing Machine such that a compressive stress could be applied on the specimen. The other cell identical in design was placed outside the universal testing machine such the specimen therein was under zero stress.

Hollow 4"x 8" cylindrical specimens were used such that water could permeate under pressure through the outer wall and be collected in the inner hollow core. The collected water in the hollow core was then drained out to a collection reservoir and its mass was measured accurately as a function of time using a computer controlled scale. Under steady-state conditions, the coefficient of permeability (K_w) was obtained using the Darcy's equation (Equation 4.1).

6.2 CONCLUSIONS

1. For concrete prematurely loaded at an age of 1 day to an applied stress of $0.2f_u$ where f_u is the compressive strength at the age of test, a decrease in the permeability was noted, while the same concrete loaded to a stress of $0.4f_u$ demonstrated a significant increase in the permeability. Thus, there appears to be a threshold value of stress beyond which significant increases in the permeability can be expected.
2. At an age of 3 days, an applied stress of $0.3f_u$ was also seen to decrease the permeability. However, the same level of stress ($0.3f_u$) when applied to a specimen that was prematurely loaded to $0.4f_u$ at an age of 1 day significantly increased the permeability relative to an unloaded specimen. Loading history, therefore, appears to be an important factor in governing the permeability of stressed concrete.
3. The replacement of cement with 25 and 50 percent fly ash content reduced the compressive strength of concrete at early ages. But beyond 7 days, the rate of changes in compressive strength of fly ash concrete was higher than that of plain concrete specimens.

4. The higher the replacement level of fly ash, the higher the permeability of concrete at early ages. However, the rate of decrease of permeability was higher for HVFA mixes. In the end, the HVFA mixes showed comparable permeability to plain, control concrete mixes.

6.3 RECOMMANDATION FOR FUTURE RESEARCH

There are at least three directions in which future researches can be expanded.

1. In this program, the changes in water permeability were monitored at early ages under a constant level of applied stress. The experimental results showed that the permeability of concrete was highly affected by applied stresses and seriously compromised by cracking at early ages. But, the exact influence of an externally applied stress on the permeability of concrete remains poorly understood. Questions such as what level of stress is acceptable and at what age remain unanswered.
2. Results indicated that the presence of a compressive stress below a certain threshold value decreased the permeability, but when the applied stress exceeded this threshold, a significant increase in the permeability occurred. In this context the influence of mix proportions, curing condition, supplementary cementing materials, and fibers on the threshold stress need to be studied.
3. Fly ash as a supplementary cementing material can retard both strength gain and setting time and produce concrete with high initial permeability in its early ages. The permeability of HVFA concrete should be measured as a function of stress level, age, curing conditions, etc. Such a test program will assist us in designing

mixes that can maintain a certain level of water tightness at a certain age and under a certain level of applied stress.

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