DEVELOPMENT OF CONSTANT HEAD PERMEABILITY APPARATUS FOR CEMENT MORTARS

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1988

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 1992

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ACKNOWLEDGEMENTS

I sincerely appreciate the help of those who helped during this study. I would like to thank and express my appreciation to Dr. M. E. Ayers, my major advisor for his instruction, advice, time and continuous encouragement during my graduate study. Appreciation is also extended to Dr. S. A. Ahmed and Dr. G. D. Oberlender for serving on my committee.

I would like to offer special thanks to my friends for their cooperation and assistance.

I am deeply grateful, and wish to express my appreciation to my family, especially my parents whose support and encouragement made my education possible.

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CHAPTER I

INTRODUCTION

The permeability of concrete is a property of interest to nearly all designers of concrete structures. Concrete is extensively used in hydro-electric power development, harbor works, irrigation, water supply, isolation of waste materials and other types of construction projects. It is essential that concrete be able to fulfill its design function, over a period of years, without excessive deterioration due to environmental factors. The permeability of concrete is a significant factor in determining the durability of concrete. A lack of durability in concrete structures has become a serious problem in many parts of the world.

Numerous studies [1-16] have evaluated the permeability of concrete. These studies include a myriad of methods for conducting permeability tests. The majority of these test methods have proven satisfactory in evaluating the permeability of concrete. It has been shown that concrete durability is closely related to its environment and its permeability.

Basis of Study

The permeability of concrete can be defined as the ease with which water (or other fluids) can move through concrete, thereby in process transporting aggressive agents in some cases. The permeability dictates the rate at which aggressive agents can penetrate and react with concrete. The aggressive agents may be gases (CO_2, SO_3 etc---), or liquids (acid rain, acidic water, sea water, sulphate rich water, deionized water etc---). Therefore the permeability of concrete is a critical factor in many types of adverse reactions, including:

a) Sulphate Attack- Due to water movement containing sulphate ions into the concrete. The Sulphates react with $Ca(OH)_2$ and calcium aluminate hydrate in the cement matrix. The products of the reaction, gypsum and calcium sulphoaluminate, have considerably greater volume than the compounds they replace. This leads to the expansion and ultimate cracking of the effected concrete. The damage usually begins at the edges and corners, followed by progressive cracking and spalling towards the interior, thereby reducing the concrete to a friable or rubberized state.

b) Frost Attack- Permeability determines the relative ease with which concrete can become saturated with water. Therefore, it increases the vulnerability of concrete to frost attack. As the temperature of saturated hardened concrete is lowered, the water held in the capillary pores in the cement paste freezes and expansion of the concrete takes place. If subsequent thawing is followed by refreezing, cumulative expansion occurs. When the dilating pressure in the concrete exceeds its tensile strength, damage occurs. The extent of the damage varies from surface scaling to complete disintegration. Lenses of ice are formed beginning at the exposed surfaces of the concrete and progressing through its depth.

c) Alkali-Aggregate Reaction- Due to the movement of water transported alkali ions to aggregates and resulting in the formation of expansion gels. The most common reaction is between the active silica constituents of the aggregates and the alkaline hydroxides derived from the alkalis (Na_2O and K_2O) in the cement. As a result, an expansive alkali-silicate gel is formed, near the surface of the aggregates. The gel is confined by the surrounding cement matrix, resulting in an increase in internal stresses within the concrete. Eventually, this expansion leads to cracking and disruption of the cement matrix.

d) Acid Attack- In certain circumstances, SO_2, CO_2 and other acidic gases present in the atmosphere react adversely with concrete. These gases form weak acids in the presence of water and subsequently dissolve the cement matrix. This can result in a drastic reduction in the strength of concrete over time.

d) Fire Resistance- Escaping steam from heated concrete mass often results in surface spalling.

e) Corrosion of Steel- The ingress of water and air in reinforced concrete will result in the corrosion of reinforcing steel. In the case of deicing salts, dissolved chloride ions corrode the steel, resulting in an increase in its volume. The increased volume results in internal stress building and cracking and spalling of the concrete cover.

Permeability of a well compacted concrete is a function of the paste and aggregate permeabilities, and the relative proportion of the cement and aggregates [20]. A number of deleterious processes in concrete are related to pore structure. In particular, they are related to the diffusion characteristics and permeability of the concrete. It is important, therefore, to obtain information on such properties of concrete within a short period of time.

Statement of Problem

The permeability of concrete is an important factor influencing the durability of concrete structures. Extensive research concerning the permeability of concrete has been conducted worldwide. Permeability test data are widely available, however, a standardized procedure for determining the permeability of concrete does not currently exist. Numerous methods and a variety of apparatus have been developed to measure the permeability of concrete. McMillan and Lyse [1], Norton and Pletta [2], Ruettgers, Vidal and Wing [3], Tyler and Erlin [6], and Meulen and Dijk [7] have conducted extensive research in the determination of concrete permeability. The various apparatus used by these researchers were similar in that all of them measured the flow rate of water under pressure through concrete specimens after steady state flow conditions had been reached.

The major problems generally encountered in performing permeability tests on concrete include, a) excessive time required for each test, b) leakage at sample/apparatus interface, c) extremely low water flow, d) the effect of air in the Portland Cement Concrete voids, e) expense of equipment, (f) specialized sample requirements, and (g) general difficulties in testing.

The above problems indicate that there is still a need to develop a standard test method and apparatus which can account for the aforementioned factors and give valid and reliable permeability measurements.

Objective of Study

The objective of the study is twofold:

1) Development of a test apparatus and procedure to

determine the permeability of cement mortars.

2) Determine the correlation between the permeability test results and the results obtained with standard test method ASTM C 642-90.

Scope of Work

The scope of the work includes:

1) Development of a test apparatus for permeability measurements.
2) Casting of cylindrical specimens for permeability measurements of 0.4, 0.5 and 0.6 water-cement ratios, and two curing periods of 1 and 7 days, keeping a constant sand-cement ratio of 3:1.
3) Casting of cube specimens for standard test method ASTM C 642-90 with the same water-cement ratios, curing periods, and constant sand-cement ratio as for permeability specimens.
4) Establishment of a correlation between permeability values obtained from the tests, and the volume of permeable voids obtained from ASTM C 642-90.

CHAPTER II

LITERATURE REVIEW

Background

There is a growing awareness of the important role that permeability plays with regard to the long term durability of concrete structures. It is now recognized that durability is often the determining factor in the life of a concrete structure, and that durability may be directly related to the permeability of the concrete. If an aggressive substance, be it water, sulphate, chloride ions or other materials can be isolated from concrete by virtue of low permeability, then associated problems such as freeze thaw deterioration, corrosion of reinforcement, and the formation of expansive components may be alleviated. Therefore, there has been interest both in determining the permeabilities of conventional concretes or cement mortars, and in the development of improved concretes having very low permeabilities.

Concrete technologists have generally adopted a broader definition of "permeability" than that associated with saturated flow under a hydraulic gradient. Permeability is viewed as the ability of a given concrete to resist intrusion of a particular substance (be it liquid, gas ions etc.). This ability may be expressed in absolute units of flow (eg. cm/sec), by the amount of substance deposited in a given time, or as a relative ranking derived from testing.

The need for accurate data concerning concrete permeability dates from the 1930's, when designers of large hydraulic structures required information on the rates of water passage through concrete under the influence of relatively high hydraulic heads. Numerous methods and test apparatus were developed to determine the factors influencing hydraulic permeability. The effects of curing and mix design parameters on permeability were determined, as well as the flow of substances through concrete other than water (methane, nitrogen, oil etc.).

Under conditions, other than those of saturated fluid flow, transport of substances through concrete can occur by a variety of different mechanisms. These may include: 1) capillary attraction, 2) vapor transmission , or 3) ionic diffusion.

There is currently much concern with corrosion of reinforcing steel promoted by chloride ions which penetrate through the concrete cover and eventually reach the reinforcement. Numerous simple and rapid determination procedures for chloride ion permeability currently exist.

While a need for inclusion of permeability limits in specifications for certain concrete applications is gradually being recognized, the existence of numerous laboratory and field test procedures create confusion on the part of the user as to what should be specified.

Overview of Previous Research

Civil engineers have long been interested in the rate of flow of water through Portland Cement Concrete (PCC). In 1929, McMillan and Lyse [1], performed numerous tests at the research laboratory of the Portland Cement Association. The purpose of this study was to measure the water-tightness or permeability of concrete mixtures, as a part of a general investigation concering the factors affecting the durability of concrete. The type of apparatus used in these tests was determined by research limitations imposed by the magnitude of the proposed program, and also by the large number of variables to be investigated. Their first concern was that the apparatus could be easily duplicated, and be of such design that the specimens could be inserted and removed with a minimum loss of time. Tests were conducted on concrete specimens cut from 6-inches (150-mm) in diameter and 12-inches (300-mm) high concrete cylinders, so that the permeability data could be related to compression test results on this size specimen. Moreover, the results were based on the volume of water actually passing through the concrete. An apparatus was developed which permitted the use of concrete discs 6-inches (150-mm) diameter and of thicknesses upto 4-inches (100-mm). The apparatus consisted of a number of individual interconnected cells. Water was passed through the specimens under constant pressure facilitated by compressed air. The schematic of the apparatus is shown in Figure 1 [Appendix B].

A number of tests were performed on concrete and mortar specimens. The concrete specimens evaluated were 6-inches (150-mm) in diameter and 4-inches (100-mm) thick, and were tested at a pressure of 80 psi at various stages of curing and for various water-cement ratios. Mortar specimens were 6-inches (150-mm) in diameter and 1-inch (25-mm) thick, and were tested at 20 psi at various sand-cement ratios. The tests were conducted for a total of 48 hours following 28 days of moist curing. The values obtained for concrete and mortar specimens were consistent in all regards, giving an indication that the results were reliable.

In 1931, Norton and Pletta [2], presented a paper at the 27th Annual American Concrete Institute (ACI) meeting that described a permeability testing device of their design. The concrete samples evaluated in this device had water-cement ratios ranging from 0.62 to 1.2. It was concluded that this method produced reliable results, but was applicable only to gravel concrete and could not be used for different types of concrete. In 1935, Ruettgers, Vidal and Wing [3], published a report which was considered to be the basis for estimating the permeability of concrete under saturated flow conditions when subjected to large hydrostatic heads ranging from 300 to 1000 ft. The apparatus was developed for mass concrete permeability measurements. The device was suitable for concrete specimens with large sized aggregates approximately 9-inches (225-mm), with high water heads of about 400 psi. The apparatus was made of cast nickel steel, and the specimens tested were 18-inches (450-mm) in diameter and 24-inches (600-mm) high cylinders. The sealant used to secure the sample in the apparatus was a commercial asphalt pipe joint compound. Evidently there were numerous leaks in the set-up which were difficult to detect. A detailed study of the probable errors involved in the values of the coefficients of permeability indicated that the test results were subject to a probable error for a single specimen of about 25 percent. These test results were of great value for their intended purpose. However, the method employed cannot be generally applied nor can the test results be used for estimating low-head permeability of different types of concrete.

In 1937, Wiley and Coulson [4], stated that most permeability investigations were using equipment that was "..so costly and time consuming as to make it prohibitive." They described a "flower pot" method of permeability measurement in which a container was cast concrete. The rate at which water in the container had to be replenished was used to calculate permeability. Water-cement ratios ranging from 0.35 to 0.75 were used in their study. The results when evaluated showed major errors. The permeability coefficients calculated were 100 to 1000 times larger than those estimated from Boulder Dam tests [3], for similar mixes and water cement ratios. It was concluded that the method has merits where the movement of liquids in the pores is caused primarily by the capillary forces rather than by hydrostatic pressure.

In 1951, the United States Army Corps of Engineers [5], determined the permeability of lean concretes used in dams. Their method used positive pressures of 100 or 200 psi to force water through the specimens. Cylindrical specimens 14 1/2-inches (362-mm) in diameter and 15-inches (375-mm) high were used. Forms were made of No. 26 gage galvanized sheet steel with integral bottoms. Sealants used to secure the specimens in the container were paraffin-rosin compound and hot 200-300 penetration asphalt. The test results obtained were generally not applicable to low-head conditions and concretes of different formulations. A schematic of the apparatus is shown in Figure 2 [Appendix B].

It was clear that a more rapid and universally adaptable method of measuring concrete permeability was required. In 1961, Tyler and Erlin [6], proposed a method in which the rate and the total volume of pressurized water forced into a 6-inches (150-mm) diameter and 12-inches (300-mm) high concrete specimen was measured. Pressures ranging from 40 psi to 5000 psi were used. The low pressure apparatus was essentially the same as used for high pressure determinations. All fittings were made leak proof, including the top of pressure vessel by means of molded rubber O-rings. The drawbacks of this apparatus were a lack of reproducibility and the values of the measured permeability coefficients were generally well below those that had been obtained by other methods of permeability testing. It was suggested by the developers that this method can be used for the determination of the relative permeabilities of different concrete mixtures.

Test procedures and equipment development favored the use of small specimen sizes as compared to previous methods. Innovations were also evident in new methods of sealing the apparatus/sample interfaces.

In 1969, Meulen and Dijk [7], developed a permeability apparatus, in which the specimen is placed in such a manner that water or air, under pressure, can be applied to one face and the amount of fluid that permeates through the specimen measured. The apparatus consisted of a permeater pot with a brass ring bolted to its base. The ring was provided with two circular solid neoprene sealing rings, one to seal the ring to the base of the permeameter, and other to provide a seal between the ring and a circular epoxy resin casting surrounding the specimen. The epoxy resin ring was cast around the specimen and allowed to harden before the specimen was inserted in the brass ring on the base of the permeameter. The method was found to be an easy and reliable means of sealing permeability specimens into permeameter pots. An added benefit was that the samples could be used repeatedly without further preparation. A diagram of the apparatus, with specimen in position, is shown in Figure 3 [Appendix B].

Since the renewed interest in concrete permeability, several modifications to the test apparatus have been made. Figgs [8], developed an apparatus for estimating the air and water permeability of in-situ concrete. In this method, pressurized water is injected in a hole drilled in concrete. The water diplaces all air within the apparatus and concrete cavity, and its meniscus is brought to a convenient position in the capillary tube. The time for the meniscus to travel 50 mm (2-inches) is taken as a measure of the water permeability of concrete. During laboratory evaluations, it was determined that the modified "Figg test" suffered several drawbacks. The most important of which was a lack of control of the moisture content of the concrete and uncertainity regarding the actual volume of concrete effected (ie. the extent to which the water flows through the concrete under the conditions of the test). Additional problems related to the presence of air bubbles in the system, effective sealing, and calculation of the coefficient of permeability.

In 1983, Hope and Malhotra [9], developed a test apparatus based on the same principles as previous designs. The apparatus consisted of a series of pressure cells connected to a common hydraulic line which facilitated pressurization of the water of up to 500 psi. Each cell contained a cylindrical concrete sample 150-mm (6-inches) in diameter and 150-mm (6-inches) in height, through which water passed in the longitudinal direction. The equipment design and preparation of the specimens ensured one-dimensional flow. The volume of water passing through the concrete sample per minute was measured and recorded. This test method and apparatus was considered to present a valid means of determining the permeability coefficients for concrete mixes with a wide range of water-cement ratios and air contents. Details of pressure cells and the connection of cells to pressure vessel are shown in Figures 4 and 5 respectively [Appendix B]. In this method, the hydraulic gradient could be easily varied, fluids other than water could be used, and the device could be modified to simulate actual field conditions to which the concrete was subjected. It was recommended that this test method and apparatus be adopted by The Canadian Standards Association as a Canadian Standard Test Method.

In 1988, Bisaillon and Malhotra [10], modified the apparatus developed by Hope and Malhotra [9]. Modifications were made in both sample preparation and the hydraulic system. In the original test procedure, the sides of the concrete samples were sealed with a fibreglass resin compound, to ensure uniaxial flow. However, this procedure was cumbersome and the resin occasionally developed cracks. Therefore, the resin was replaced by an epoxy mortar, which gave satisfactory performance. The original vessel consisted of two closed hollow cylinders fitted with collars, which were bolted together. The top section was connected directly to a nitrogen tank, with the bottom section connected via water filled lines, to the pressure cells. When the gas pressure in the top of the vessel was increased by means of a valve in the nitrogen tank, the diaphragm was pushed downwards pressurizing the water in the lower half of the vessel. This increased the water pressure in the lines and, in turn, the pressure in each cell. The intent of the diaphragm was to prevent the dissolution of nitrogen by water under pressure.

It was found that the diaphragm did not always fulfill its intended function, and nitrogen leaks occured, forming bubbles in the water. Thus the measurement of water in the capillary tube was effected. The nitrogen pressure system was replaced by a constant pressure oil system which could provide pressures of up to 500 psi in increments of 3 psi. The modifications made to the pressure system resulted in making the tests relatively simple to set-up. The use of epoxy mortar eliminated cracking in the concrete jackets. However, these modifications did not contribute to any significant decrease in the variability of the permeability test results.

In 1987, Tanahashi, Ohgishi, Ono, and Mizutani [11], developed a new testing apparatus capable of directly measuring the permeability of structural concrete. This apparatus was intended to establish a new method for the evaluation of the quality and durability of structural concrete in terms of water-tightness. The effects of fluidity (slump) and mix proportions on permeability were investigated, using concrete samples of disc and hollow-disc types. At two locations of the construction site the effects of quality variation due to mixing of fresh concrete, transportation, and placing on the permeability of concrete were investigated. This was done by sampling at the lower and upper parts of the wall and the floor of the structural concrete.

The test apparatus consisted of two systems; a pressurized water feed system and a pressure regulating system. Both systems were interconnected with a simflex tube. Two types of specimens were evaluated; a) disc type, 150-mm (6-inches) in diameter and 40-mm (1 1/2-inches) high, b) hollow disc type, inner diameter 35-mm (1 3/8-inches), outer diameter 150-mm (6-inches) and thickness of 40-mm (1 1/2-inch). It was concluded that a comparative examination and evaluation of test results obtained from this testing device in conjunction with theoretical permeability determinations could be used to ascertain the acceptability/unacceptability of the water-tightness of concrete. A schematic illustration of the apparatus is shown in Figure 6 [Appendix B].

Janssen [12], developed an apparatus for laboratory permeability measurements of concrete samples obtained from existing highway pavements. PCC cores of 75-mm (3-inches) diameter and 80-mm (3 1/8-inches) long were used. Samples were sealed in a brass sample ring 90-mm (3 1/2-inches) in diameter and 80-mm (3 1/8-inches) long using Dow-Corning concrete sealer which was allowed to cure overnight. Leakage between the cell top and base and the brass sample ring was eliminated by rubber O-rings and a thin film of silicone vacuum grease. The water reservoir was made of acrylic tube 100-mm (4-inches) in diameter and 6-mm (1/4-inches) wall thickness. A regulated, air pressure source was used to pressurize the system to approximately 40 psi. A cross section and schematic of the apparatus are shown in Figures 7 and 8 repectively [Appendix B]. This test method gave accurate and reliable results for a wide range of permeabilities and could be used with laboratory or field samples.

Ludirdja, Berger and Young [13], after trying various modifications to existing equipment, undertook an entirely new approach. They used gravity induced flow to measure permeability. Test specimens were obtained from saw cutting either laboratory test cylinders or field cores. This apparatus has proved to be reliable and efficient, but further modifications of the apparatus are in progress. A schematic view of two versions of the apparatus are shown in Figures 9 and 10 repectively [Appendix B].

Sullivan [14], developed an apparatus which could accomodate up to seven samples simultaneously. The apparatus featured a computer controlled data acquisition system, thereby eliminating a souce of operator error. The system consisted of seven core holders, which could handle cylindrical samples ranging from 1 1/2-inches (38-mm) to 4-inches (100-mm) in diameter, and from 4-inches (100-mm) to 11-inches (275-mm) in length. The confining and driving pressures could be independently varied up to 4,000 psi. Stainless steel tubing was used so that the test medium could be either liquid (including brine) or gas. The automated control system was a Hewlett Packard 200 series computer and a model 3497 data acquisition/control unit. The computer was programmed to compute permeability and plot the results. Further improvements to the test system are still in progress.

As previously mentioned, much data are available in the literature, but there is no recognized standard test method. Most permeability tests require the application of high pressures necessitating expensive equipment. The tests must be conducted by skilled technicians further adding to the expense. In addition, there are numerous practical problems which make PCC permeability measurements difficult.

Problems with Permeability Measurements

The fact that numerous PCC permeability measurement methods exist indicates that there are numerous problems encountered when measuring concrete permeability as indicated below. Research is on going to develop test methods that counter these problems.

Specialized Sample Requirements. Tests that require specially made samples are currently not applicable to field cores. Therefore they may not be realistic for special finishing and sealing applications.

Quantity of Flow. Typical permeabilities for medium and high strength portland cement concrete are approximately 10^{-10}cm/sec or less [20]. For low hydraulic gradients and reasonable sample sizes, the quantity of flow through the sample is small. This was recognized by McMillan and Lyse [1], who resorted to reducing the moist curing period of their PCC samples to increase the permeability. This would not be applicable for field samples. Several solutions include; longer time periods for measuring flow, high hydraulic gradients as used by the U.S. Army Corps of Engineers [5], or a combination of these.

Leakage At the Sample/Apparatus Interface. When high pressures are used to overcome the low flow problem, sealing a sample becomes quite difficult. Some researchers have resorted to tapered samples [24] which are very difficult to produce from field samples, and may still leak if not properly made.

Effect of Air in PCC Voids. Air in a small pore effectively blocks water flow through that pore [22]. Not only must a sample be saturated for reliable permeability measurements to be made, it must also remain saturated during the test. When high hydraulic gradients are used to increase the quantity of flow, the drop in pressure across the sample can cause air dissolved in the water to come out of solution, thereby decreasing permeability over time.

<u>Expense of Equipment and Difficulty of Test</u>. Due to the high cost of the equipment and the difficulty in performing permeability tests, the test is often omitted unless it is absolutely necessary. The result is a slow down in the development of new approaches and test methods.

The inclusion of permeability criteria in specifications for certain concrete applications is likely to be mandated in the future. Some specifications may require values of permeability so low that they cannot be measured by current techniques, the aim being to obtain permeabilities low enough to prevent ionic migration into concrete. In such cases more appropriate test methods may be needed.

The aforementioned problems and existence of numerous field and laboratory procedures indicate that there is still a need to develop a standardized permeability test procedure. The research conducted in this study is based on the need for developing a test method which may alleviate many of the problems previously encountered in permeability determinations.

CHAPTER III

RESEARCH METHODOLOGY

This chapter summarizes the design, assembly and operation of the permeability apparatus used in this study. The test procedure for the determination of percentage volume of permeable voids is also presented.

Test Apparatus

The permeability apparatus consists of three permeability cells and associated piping and valving. Each cell has a number of sub-assemblies that are constructed entirely of stainless steel and inert plastics. These materials effectively eliminate the corrosion problems prevalent in earlier studies. The system is capable of sustaining pressures of up to 1500 psi in all cells.

Each cell contains a cylindrical sample through which water passes in the longitudinal direction. The equipment design and sample configuration ensures one-dimensional flow.

Permeability Cells

Design Details

The permeability cells and the hydraulic system are constructed entirely of stainless steel. They are designed so the sample can be subjected to a constant, externally maintained, hydraulic pressure. Details of cell construction are shown in Figure 11 [Appendix B].

The cell consists of three parts:

1) A 127-mm (5-inches) diameter and 35-mm (1-3/8 inches) high cell base, machined in the center so that the sample cylinder is a snug slip fit. An O-ring groove is cut in the sample base for a neoprene O-ring to ensure a water tight seal. A fluid feed is also provided in the base so that water is delivered at a predetermined pressure across the entire sample face.
2) A sample cylinder 57-mm (2 1/4-inches) outside diameter and 50-mm (2-inches) long, with fine threads machined at an inside diameter of 32-mm (1 1/4-inches.). Threaded annular rings 32-mm (1 1/4 inches) diameter are used to secure both sides of the sample in the sample cylinder. Neoprene O-rings are forced against the sample and the cylinder wall thereby eliminating sample/cylinder leakage.
3) The cell top is of the same dimensions as the cell base with only a slight modification. A 1/4-inch (6-mm) tapped hole is provided to allow attachment for a Nylon tube fitting reamed to accept micro-pipette. The micro-pipette is used to measure the amount of flow through the sample in a specified

time interval.

The cell components are assembled using three (3), 1/4-inch (6-mm) bolts. These bolts ensure a tight seal between the cell base, sample cylinder and cell top.

Assembly of Permeability Unit

The permeability apparatus consists of three permeability cells and associated piping and valves. The cells are permanently attached to a frame mounted on a laboratory counter. A schematic of the apparatus is shown in Figure 12 [Appendix B].

All cells are connected to the fluid delivery system by means of 1/4-inch (6-mm) diameter, Type 304, seamless stainless steel high pressure tubing. Each cell is connected to a 1/4-inch (6-mm) stainless steel high pressure ball valve which controls the flow of water into the cell. Water is stored in a stainless steel cylinder which is maintained half full to account for elevation head. A one inch thick layer of highly viscous mineral oil is placed between the water and air to prevent air entrainment in the water. The top of the cylinder is connected to a pressure gage and pressure regulating valve, which in turn is connected to the air supply. All fittings in the unit are of stainless steel and can withstand high pressures of up to 1500 psi. The apparatus is constructed to allow the use of corrosive fluids if desired.

Test Program

The mortar specimens used in this study had constant sand-cement ratio of 3:1. The cement used was Type I Portland Cement and the fine aggregate was natural siliceous sand. The gradation curve for the fine aggregate is shown in Figure 13 [Appendix B]. Water cement ratios of 0.4, 0.5 and 0.6 were used in the tests, and 1 and 7 day curing periods were evaluated.

Sample preparation consisted of casting 12 samples for each water-cement ratio. Six (6) samples were made three (3) each for 1 and 7 days curing respectively (Batch B1). Another six (6) samples of the same water-cement ratio were made and designated as Batch (B2). Different batches of the same water-cement ratios and curing period were used as a measure of the variation of permeability values due to sample preparation. The specimens, after casting were placed in a moist curing room maintained at 100 percent relative humidity for 12 hours. Following the initial curing period they were removed from the moist room and immersed in water until test time.

Three samples of each water-cement ratio and curing period were tested in the permeability cells under a constant pressure head of 50 psi. Tests were conducted for 48 hours, and the amount of water flowing through the samples during this time was measured and used in the calculation of permeability coefficients. This relatively short duration test was used because, unless the test is carried to the point where the rate of flow remains practically constant, it is very important that comparisons of different variables be made at some definite time. Therefore, comparisons were made on the basis of flow in the first 48 hours.

The testing program also included preparation of samples for relative permeability testing. Tests were conducted in accordance with the standard test method specification ASTM designation C 642-90 [32]. Six (6) samples for each of the water-cement ratios 0.4, 0.5 and 0.6 were prepared, three (3) each for 1 and 7 days curing periods respectively. Relative permeability values were determined in terms of percentage volume of permeable voids.

Preparation and Casting of Test Specimens

Samples 30-mm (1 1/4-inches) in diameter and 10-mm (3/8-inch) high were cast for testing in the pressure cells. A minimum of 12 samples were made for each water-cement ratio tested. Three water-cement ratios and two curing periods were used with a constant sand-cement ratio. Type I Portland Cement was used and the fine aggregate was natural siliceous sand. The moisture content of the sand was checked prior to the preparation of the samples. The sand was kept in an air-tight container so that the moisture content did not vary during sample preparation. Mixing was done by hand.

Molds for the samples were made of plexiglass turned down on a lathe to a specific configuration as shown in Figure 11. The edges of the molds were chamfered for the placement of neoprene O-rings.

Before placing the molds on the cast iron base plate the top of the plate was thinly covered by a Silicone lubricant, so that the samples would not stick to the plate. The joint between the mold and base plate was brushed with melted paraffin and allowed to cool to facilitate a water-tight joint.

The samples were placed in two layers and rodded 16 times per layer. The mortar was struck-off to flush with the top of the mold by drawing a straight edge with a sawing motion over the length of the mold.

Upon completion of molding, the samples were placed in a moist room maintained at 100 percent relative humidity for 12 hours, with their upper surfaces exposed to moist air but protected from dripping water. The samples were then removed from the moist room and immersed in water until test time. This method was employed so that the samples would be fully saturated when tested since accurate permeability determinations can only be made when the mortar is fully saturated.

Test Procedure for Permeability Measurement

Tests were conducted by pressurizing the water through the cell base. The amount of water passing through the sample was then measured by means of a micro-pipette connected to the cell top.

Leakage at the sample/cylinder interface was a major problem during initial testing. This problem was due to the use of high pressure and sample placement. Several methods for sample placement in the cylinder were evaluated. For example, initial tests where the sample was placed between the porous stones created sealing problems at the sample/cylinder interface. Placing the sample at the bottom of the cylinder also caused leakage and non-uniform distribution of pressure. The problem was solved by coating the fine threads of the cylinder with Dow Corning High Vacuum grease. The sample was placed at the center of the cylinder and neoprene O-rings pressed into the chamfered edges of the sample mold. The threaded annular rings were then tightened, forcing the sample against the O-rings at both ends, ensuring a leak-proof seal. Carborundum porous stones were placed in the top and base cells to ensure uniform pressure distribution over the entire sample area.

Problems with leakage at sample/mold interface under high pressures were also encountered. They were alleviated by roughening the inside of the molds with coarse sand paper. This was done to provide a better mechanical bond between the mortar and the mold surface. Low pressures were used to counter erosion problems experience with the 1-day cured samples.

After the sample was in place, the cylinder was fitted in the cell base. Water was injected in the cylinder by means of a seriological syringe to help eliminate trapped air, thereby reducing the time required to initiate flow through the sample. Following this the cell top was placed on the cylinder and the assembly bolted together for a leakproof fit.

A constant pressure head of 50 psi was maintained during the test. The pressure was regulated by a pressure regulating valve connected to the air supply line. All three cell control valves were opened and water allowed to flow through the cell bases.

Problems due to entrapped air in the system were also encountered. This was solved by using a vacuum pump to purge air from the system. Vacuum was applied through the plug on top of the cell. This proved to be effective and any air trapped in the system was removed.

In all cells the flow through the samples was measured by observing the fluid rise in the pipette as a function of time. Permeability was calculated using Darcy's law.

Darcy's Law for Uniaxial Water Flow

Darcy's law for uniaxial water flow through a saturated medium states that:

$$q = A\ k\ i \qquad (1)$$

Where,

q = Volume of water flowing per unit time (cm^3/sec.)

A = Cross-secional area of the sample (cm^2)

k = Coefficient of permeability (cm/sec.)

and,

i = Hydraulic gradient across sample (cm head/cm)

= (pressure at bottom of sample minus - pressure at the top of sample) divided by the height of the sample.

The pressure at the base of the sample was taken as 50 psi gage and at the top as zero.

The pressure at the bottom can be expressed as:

50 x 7031 x 0.5 = 3516 cm (1384 inches) of water

For sample with a diameter of 30-mm (1 1/4-inches) and 10-mm (3/8-inch) high, the values of A, i, k in the above equation are as follows:

$$A=\frac{\pi x D^2}{4}=\frac{3.14x3^2}{4}=7.068\,cm^2 \qquad (2)$$

$$i=\frac{3516-0}{1.0}=3516\,cm\text{-}head/cm \qquad (3)$$

$$k=\frac{q(cm^3/s)}{7.068(cm^2)x3516(cm/cm)}=\frac{q}{24851}\,cm/s \qquad (4)$$

The validity of the test method, which depends primarily on the rate at which the water flows through the sample and the accuracy of the calculations for determining permeability coefficients, is subject to a number of assumptions and simplifying approximations.

The principal assumptions were as follows:

1) The degree of saturation at start of test is uniform throughout the specimen.

2) The penetration of water is uniform.
3) Back pressure from air compressed within the mortar sample is negligible.
4) Temperature effects are negligible.
5) Compressibilities of the specimen are neglected.
6) Humidity within the specimen at time of test is 100 percent (no tension in water).
7) Flow through the sample is laminar. Because PCC permeability values are not often needed to a high degree of precision, and the gradients are low, the laminar/turbulent error is ignored.

Determination of Relative Permeability Using the ASTM C 642-90 Procedure

The relative permeability of the mortar specimens was determined in order to compare the test results obtained from permeability apparatus. The validity of the coefficient of permeability determined with the apparatus can then be assessed in terms of a standardized test procedure.

<u>Sample Preparation and Curing</u>

Cube samples 2-inches x 2-inches (2.54-cm x 2.54-cm) were prepared. Six (6) samples of w/c ratios 0.4, 0.5 and 0.6 were made with a constant sand-cement ratio of 1:3. Mixing was done by hand. Standard test method of ASTM designation C 109-88 [31] entitled "Compressive Strength of

Hydraulic Cement Mortars" was used for casting and curing of cube specimens.

Determination of Relative Permeability

The ASTM specification C 642-90 [32] entitled, "Specific Gravity, Absorption and Voids in Hardened Concrete" was used to determine the relative permeability of the specimens in terms of percent volume of permeable voids. The procedure is outlined below:

1) The specimens were weighed and oven dried for a minimum of 24 hours at a temperature of 100 - 110 degrees C. After removal from the oven, the specimens were allowed to cool in dry air and were weighed. The drying procedure was repeated until the difference between two successive dry weights was less than 0.5 %. The last dry weight was designated as (A).
2) After cooling, the specimens were immersed in water for approximately 48 hours. The surface dry weight of the specimens was then obtained and designated as (B).
3) Following step 2, the samples were kept in boiling water for approximately 5 hours, and then allowed to cool for at least 14 hours. The surface dry weight was taken and designated as (C).
4) After immersion and boiling, the specimens were weighed in water and this weight was designated as

(D).

5) The percentage volume of permeable voids was determined from the relationship:

$$V_p = \frac{(C-A)}{(C-D)} x100 \qquad (5)$$

Where,

V_p = volume of permeable voids-%

A = wt. of oven dried sample in air in gms.

C = wt. of surface dry sample in air after immersion and boiling in gms.

D = wt. of sample in water after immersion and boiling in gms.

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

This chapter summarizes the test results obtained from permeability measurements and the ASTM C 642-90 procedure. Analysis and discussion of the test results is also presented.

Permeability Test Results

Effect of Duration

Permeability tests were conducted on mortar specimens with three different water-cement ratios and two curing periods. In all the tests it was found that the flow reduced as the test duration increased, the rate of change depending on the water-cement ratio and the age of the specimen.

Figures 14 through 25 [Appendix B] show the average flow-time curve for mortar specimens from different batches, with water-cement ratio 0.4, 0.5 and 0.6. Each curve represents the average of three specimens. The individual points show the flow per hour, beginning from the time the test was started at the age of 1 or 7 days.

It is observed from the Figures 14 through 25 that the flow is decreasing continuously. These curves show a highly consistent flow from day to day. The flow decreases very rapidly on the first day and then approaches a relatively constant rate of decrease. This trend is very evident for the 0.5 and 0.6 w/c ratio. The 0.4 w/c ratio samples show a more uniform decrease throughout the duration of the test. Therefore, unless the test is carried out to the point where the flow rate is relatively constant, it is mandatory that the comparisons of different variables be made at a definite time. All tests were conducted for 48 hours and comparisons made on that basis. This time frame is justified by the relatively constant flow rate as shown in Figure 26 [Appendix B]. This figure shows the variation in flow rate as a function of w/c ratio for several time periods. These results were obtained from a group of tests conducted by McMillan and Lyse [1], in order to show this data trend.

On the basis of the aforementioned test results, it was concluded that for comparison of different w/c ratios, a constant time frame was used for all samples.

Figures 14 through 25 demonstrate similar trends to the McMillan and Lyse data. The flow of water during the first 24 hours is approximately 75 percent of the total flow for 48 hours, the majority occuring in the first 12 hours of the test.

The permeability of the cement is the major factor effecting the permeability of mortars. The flow of water is controlled by the size, shape and continuity of the capillary pores. The flow decreases as the hydration products gradually fill a portion of the original water filled pores.

A logarithmic relationship exists between the average flow and the duration of the test as shown in Figures 14 through 25. The equations are of the form:

$$Y = A + B \log (X) \qquad (6)$$

Where,

X = Duration of test in hours

Y = Average flow in cc. per hour per sq. cm.

A, B = The regression constant and coefficient respectively.

The linear regression coefficients and correlation coefficients are presented in Table I [Appendix A]. It is evident from an examination of the data, that the results are consistent and in agreement with previous studies [1-16].

The permeability of specimens cured for 1-day and placed in the permeability cells under 48 hours of pressurized flow, exhibited lower permeabilities than similar samples initially cured for 7 days prior to placement in the permeability cells. This behavior can be attributed to an increase in hydration rate and the alteration of the pore structure due to the flow of pressurized water through the sample. In other words, the pores in the pressurized samples are filled at a faster rate with hydration products, thereby decreasing the flow rate. For the samples immersed in water for 7 days prior to testing, the hydration process progresses normally, allowing formation of more continuous pores. Tables II and III [Appendix A] present the average flow values and permeability values as a function of the w/c ratio and curing period respectively.

Effect of Sample Preparation

An important characteristic of the permeability apparatus evaluated in this study is its extreme sensitivity. Table IV [Appendix A] shows calculated permeability values for the various samples, and the coefficient of variation within each batch for the same w/c ratio and curing period. The variation within each batch is typically in the range of 10 to 20 percent. The variation is relatively constant within each batch but the variation between batches is somewhat large. The average coefficient of variation between batches is on the order of 35 percent. This large variation can be attributed to the sensitivity of the test procedure. Factors such as sample size, sample preparation, curing and other factors, which materially effect permeability, are very important. Differences in the temperature of the water, minor variations in pressure, and discontinuities in the sample can have an appreciable effect on the flow and calculated permeability.

Due to the aforementioned concerns companion specimens were cast on different days in order to minimize sample preparation/curing errors. Six (6) samples were evaluated for each w/c ratio and curing period. The agreement between similar samples indicate that, regardless of the relatively large variation between the batches, the overall results can be considered reliable.

Effect of Water-Cement Ratio

The influence of w/c ratio on the permeability of mortar is seen in Figure 27 [Appendix B]. A logarithmic relationship between permeability values (k), and water-cement ratio (w/c) demonstrates a strong correlation. The relationship can be expressed as follows:

For 1-day curing:

$$k = 4.2157\text{x}10^{-08} + 9.7165\text{x}10^{-08}\ \text{Log}\ (w/c) \qquad (7)$$

For 7-day curing:

$$k = 1.2653\text{x}10^{-08} + 3.0039\text{x}10^{-08}\ \text{Log}\ (w/c) \qquad (8)$$

The correlation coefficients are 0.993 and 0.960 for Equations (7) and (8) respectively.

Permeability increases very rapidly with an increase in the w/c ratio, and at an increasing rate as the w/c ratio becomes larger. This is attributed to the fact that the w/c ratio is one of the primary factors influencing the size, volume and continuity of capillary voids. Therefore for the pastes hydrated to the same degree for a given volume of cement, the paste with the largest amount of water will have the greatest total volume of available space (sum of the volume of cement and water). As the w/c ratio increases the volume of large capillary pores in the paste matrix and the number of continuous flow channels increases, thereby increasing the permeability. The reduction of w/c ratio from 0.7 to 0.3 lowers the coefficient of permeability by a factor of one thousand [21].

Only by conducting tests through a considerable range of curing conditions, specimen sizes, pressure, and different mix proportions can the effect of w/c ratio on the permeability can be established. The results of this study show how a change in the w/c ratio effects the permeability of mortars to a limited extent.

Effect of Curing

The effect of specimen age on permeability is presented in Figure 28 [Appendix B]. The curves for the 0.4 and 0.5 w/c samples are much steeper than for the 0.4 w/c samples. The decrease in permeability of the 0.5 and 0.6 w/c samples is more rapid than for the 0.4 w/c samples of similar curing periods. This behavior is as expected as explained in the discussion on the effects of w/c ratio.

The permeability of mortar is a function of the w/c ratio and the extent to which hydration has progressed. The permeability of the cement paste appears to undergo a relatively abrupt change when, because of original w/c ratio and extent of cement hydration, the solid volume of the paste increases. The capillary pores are blocked by gel formation and become segmented. A discontinuity in the capillary pore system results when the total porosity (gel plus capillary) reaches approximately 50 percent by volume [24,25]. It is estimated that the cement pastes of 0.4, 0.5, 0.6 and 0.7 w/c ratios, require approximately 3 days, 14 days, 6 months and 1 year of normal hydration, respectively, to be discontinuous [26].

The results obtained in this study are consistent with the observations mentioned above. The permeability values of 0.4 w/c samples cured for 7 days is very low as compared with 0.5 and 0.6 w/c samples for the same curing period. This may be attributed in part to the discontinuity of the pores for the 0.4 w/c sample. There is evidence that, even at this stage, there is still a measure of continuity in the large pore system. For w/c ratios 0.5 and 0.6, the pores are still continuous, thereby resulting in higher variations in the calculated permeability.

Results of ASTM C 642-90

ASTM C 642-90 tests were conducted on 2-inch by 2-inch (2.54-cm x 2.54-cm) cube specimens identical w/c ratios and curing periods to those evaluated with the permeability apparatus. The percent volume of permeable voids was determined. The results are tabulated in Table V [Appendix A].

A logarithmic relationship between the w/c ratio and the volume of permeable voids is shown in Figure 29 [Appendix B]. There is a uniform increase in the volume of the voids as the w/c ratio increases, for the 1 and 7 day curing periods. This trend is expected as an increase in the w/c ratio effectively decreases the cement content and increases the pore space, thereby increasing the volume of voids.

The effect of specimen age on volume of permeable voids is shown in Figure 30 [Appendix B]. The slope of the curves show a consistent decrease in the volume of voids with curing time.

Comparison of Test Results

Data indicates that lowering the w/c ratio decreases permeability, and increasing the moist curing period will result in a more water-tight mortar. An objective of this study was to compare the results obtained by permeability measurements with the volume of permeable void spaces determined from ASTM C 642-90.

A logarithmic relationship exists between the permeability and permeable voids test data. This relationship is presented in Figures 31 and 32 [Appendix B] for 1 and 7 day curing periods and samples with w/c ratios of 0.4, 0.5 and 0.6. The relationship is expressed as follows:

For 1 day curing:

$$Y = -1.1626\text{x}10^{-07} + 9.8235\text{x}10^{-08}\ \text{Log}\ (X) \tag{9}$$

For 7 day curing:

$$Y = -3.1618\text{x}10^{-08} + 2.8766\text{x}10^{-08}\ \text{Log}\ (X) \tag{10}$$

Where,

X = Volume of permeable voids-%

Y = Coefficient of permeability-cm/s

The correlation coefficients for Equations (9) and (10) are 0.903 and 0.840 respectively.

There is a strong correlation between permeability and permeable voids as measured by correlation coefficients. The relationship is in agreement with a previous study [30] in which a similar comparison was made. The results of that study reported a correlation coefficient of 0.93. The ASTM C 642-90 procedure can be used to determine the relative permeability of various samples, although the test does not measure the "permeability" as conventionally defined.

The correlation between the test results suggests that the permeability test procedure used in this study is valid.

Moreover, the results indicate a good correlation with w/c ratios and curing periods. The test apparatus and procedures adopted in this study result in accurate and consistent data.

CHAPTER V

SUMMARY AND CONCLUSIONS

The overall objective of this study was the development of an efficient test apparatus and procedure to determine the permeability of cement mortars. The scope of the work included the assessment of the validity of the test results by comparing them with the results of the ASTM C 642-90 procedure. Mortar specimens were tested at three different water-cement ratios, two curing periods, and a constant sand-cement ratio and hydraulic pressure.

The permeability apparatus and procedure, as developed, performs satisfactorily, and has the following advantages and disadvantages:

1) The apparatus can accommodate three samples simultaneously, with isolation valves for each cell. The system can be easily expanded.
2) Samples can be placed and removed from the apparatus in a timely manner.
3) The use of moderate hydraulic pressures in conjunction with neoprene O-rings and the use of high vacuum grease prevents leakage around the samples.
4) The permeability cells and associated piping and

valving are of stainless steel construction and can accommodate corrosive fluids.

5) High pressure fittings allow the use of pressures of up to 1500 psi.
6) Use of a vacuum pump efficiently removes entrapped air within the system.
7) Test results are accurate and show consistent relationships between permeability values and water-cement ratio and curing time.
8) The large variation in permeability values between different batches of the same water-cement ratio and curing period is attributed to the sample preparation technique. A modification to the present method is in progress to produce more uniform samples.
9) The permeability apparatus and procedure are easy to use, accurate, and reliable for permeability measurements.

Recommendations for Further Research

Improvements to the system and recommendations for further research are as follows:

1) The equipment is currently being modified to determine the effect of confining pressure on the permeability of mortar samples.
2) Sample preparation techniques require improvements to minimize variations in permeability measurement.

3) Fluids other than water, can be used to determine the permeability of cement mortars and pastes when subjected to harsh environments.
4) The temperature effects of the fluid and the sample are thought to be an important variable. Retrofitting the device for this determination requires minimal effort.
5) More test samples should be run to justify a precision statement for this test method.
6) The number of samples required and average used to measure permeability coefficients to a certain level of confidence should be determined.
7) The equipment can be scaled up to accommodate larger samples.

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APPENDIX A

TABLES

TABLE I

REGRESSION COEFFICIENTS FOR AVERAGE FLOW VALUES AS A FUNCTION OF TIME

W/C RATIO	AGE (DAYS)	CONSTANT A	REGRESSION COEFFICIENT B	CORRELATION COEFFICIENT R
0.4	1	2.2711	-1.4107	0.994
	7	$4.1581\text{x}10^{-02}$	$-1.6301\text{x}10^{-02}$	0.996
0.4	1	1.2618	-0.85887	0.965
	7	$6.1631\text{x}10^{-02}$	$-1.6315\text{x}10^{-02}$	0.996
0.5	1	9.5681	-6.2258	0.978
	7	0.71598	-0.1334	0.985
0.5	1	4.3010	-2.7768	0.960
	7	0.3489	-0.06772	0.979
0.6	1	13.821	-9.2729	0.972
	7	0.83051	-0.14570	0.982
0.6	1	10.542	-6.9899	0.968
	7	0.78713	-0.27823	0.997

TABLE II

AVERAGE FLOW VALUES AS A FUNCTION OF WATER CEMENT RATIO AND CURING PERIOD

BATCH	SAMPLE #	W/C RATIO	AGE (DAYS)	FLOW "q" (cm^3)[a]	AVERAGE
B1	1	0.4	1	18.2	18.10
	2			16.0	
	3			20.10	
	4	0.4	7	0.95	0.96
	5			1.12	
	6			0.81	
B2	7	0.4	1	10.0	8.90
	8			7.8	
	9			8.9	
	10	0.4	7	2.2	1.92
	11			1.85	
	12			1.75	
B3	13	0.5	1	78.4	77.80
	14			90.0	
	15			65.0	
	16	0.5	7	21.9	26.12
	17			31.0	
	18			25.5	
B4	19	0.5	1	40.2	41.12
	20			37.0	
	21			46.2	

TABLE II (Continued)

BATCH	SAMPLE #	W/C RATIO	AGE (DAYS)	FLOW "q" (cm^3)[a]	AVERAGE
B4	22	0.5	7	14.0	
	23			10.9	12.62
	24			12.0	
B5	25	0.6	1	115.6	
	26			85.4	99.60
	27			97.8	
	28	0.6	7	24.7	
	29			32.2	30.96
	30			36.0	
B6	31	0.6	1	90.8	
	32			74.0	81.33
	33			79.2	
	34	0.6	7	16.9	
	35			20.0	19.96
	36			23.0	

[a] Total flow in cc. for 48 hours

TABLE III

COEFFICIENT OF PERMEABILITY AS A FUNCTION OF WATER CEMENT RATIO AND CURING PERIOD

BATCH	W/C RATIO	AGE (DAYS)	TOTAL FLOW (cm^3)[a]	k (cm/s)
B1	0.4	1	18.11	4×10^{-09}
		7	0.96	2×10^{-10}
B2	0.4	1	8.88	2×10^{-09}
		7	1.92	4×10^{-10}
B3	0.5	1	77.80	2×10^{-08}
		7	26.12	6×10^{-09}
B4	0.5	1	41.12	9×10^{-09}
		7	12.62	3×10^{-09}
B5	0.6	1	99.60	2×10^{-08}
		7	30.96	7×10^{-09}
B6	0.6	1	81.33	2×10^{-08}
		7	19.96	4×10^{-09}

[a] Total flow for 48 hours, average of 3 samples.

TABLE IV

COEFFICIENT OF VARIATION BETWEEN SAMPLES OF DIFFERENT W/C RATIO AND CURING

BATCH	W/C RATIO	AGE (DAYS)	PERMEABILITY COEFFICIENT "k" cm/s x 10^{-10}	COEFFICIENT OF VARIATION (%)
				WITHIN-BATCH
B1	0.4	1	42.3	
			37.2	11
			46.8	
	0.4	7	2.2	
			2.6	16
			1.9	
B2	0.4	1	23.2	
			18.1	12
			20.7	
	0.4	7	5.0	
			4.3	12
			4.0	
B3	0.5	1	182.6	
			209.6	16
			151.3	
	0.5	7	51.0	
			72.2	17
			59.3	

TABLE IV (Continued)

BATCH	W/C RATIO	AGE (DAYS)	PERMEABILITY COEFFICIENT "k" cm/s x 10^{-10}	COEFFICIENT OF VARIATION (%) WITHIN-BATCH
B4	0.5	1	93.6	
			86.1	11
			107.6	
	0.5	7	32.6	
			25.3	13
			27.9	
B5	0.6	1	269.2	
			198.8	15
			227.8	
	0.6	7	57.5	
			74.9	18
			83.8	
B6	0.6	1	211.4	
			172.2	10
			184.4	
	0.6	7	39.3	
			46.5	15
			53.5	

TABLE V

PERCENTAGE VOLUME OF PERMEABLE VOIDS OBTAINED FROM ASTM C 642-90

SAMPLE #	W/C RATIO	AGE (DAYS)	% VOLUME OF PERMEABLE VOIDS	AVERAGE
1	0.4	1	16.50	
2			16.90	16.40
3			15.80	
4	0.4	7	12.90	
5			13.40	13.20
6			13.40	
7	0.5	1	20.97	
8			21.70	21.20
9			20.98	
10	0.5	7	17.40	
11			17.20	17.00
12			16.60	
13	0.6	1	24.40	
14			25.00	24.50
15			24.10	
16	0.6	7	21.00	
17			20.60	20.60
18			20.30	

APPENDIX B

FIGURES

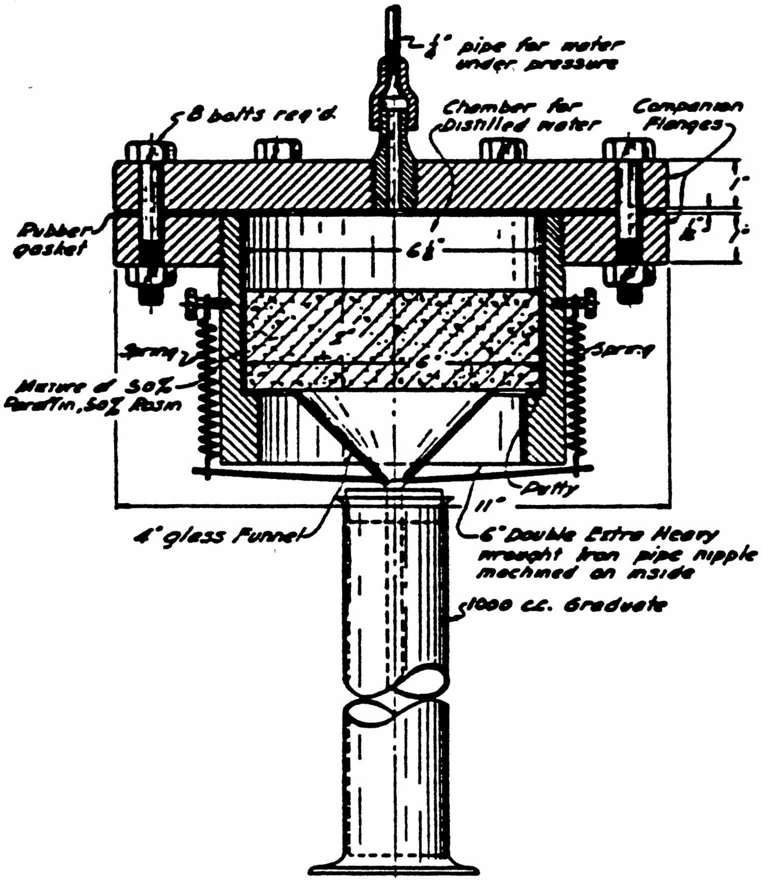

Figure 1. Schematic of the Permeability Apparatus Developed by McMillan and Lyse [1].

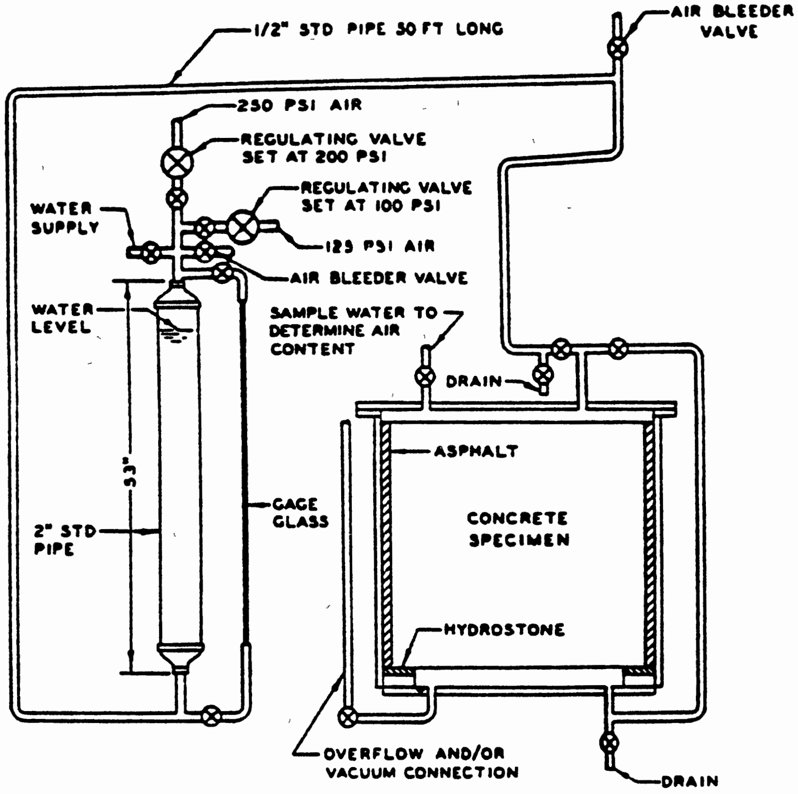

Figure 2. Schematic of the Apparatus Developed by US Army Corps of Engineers [5]

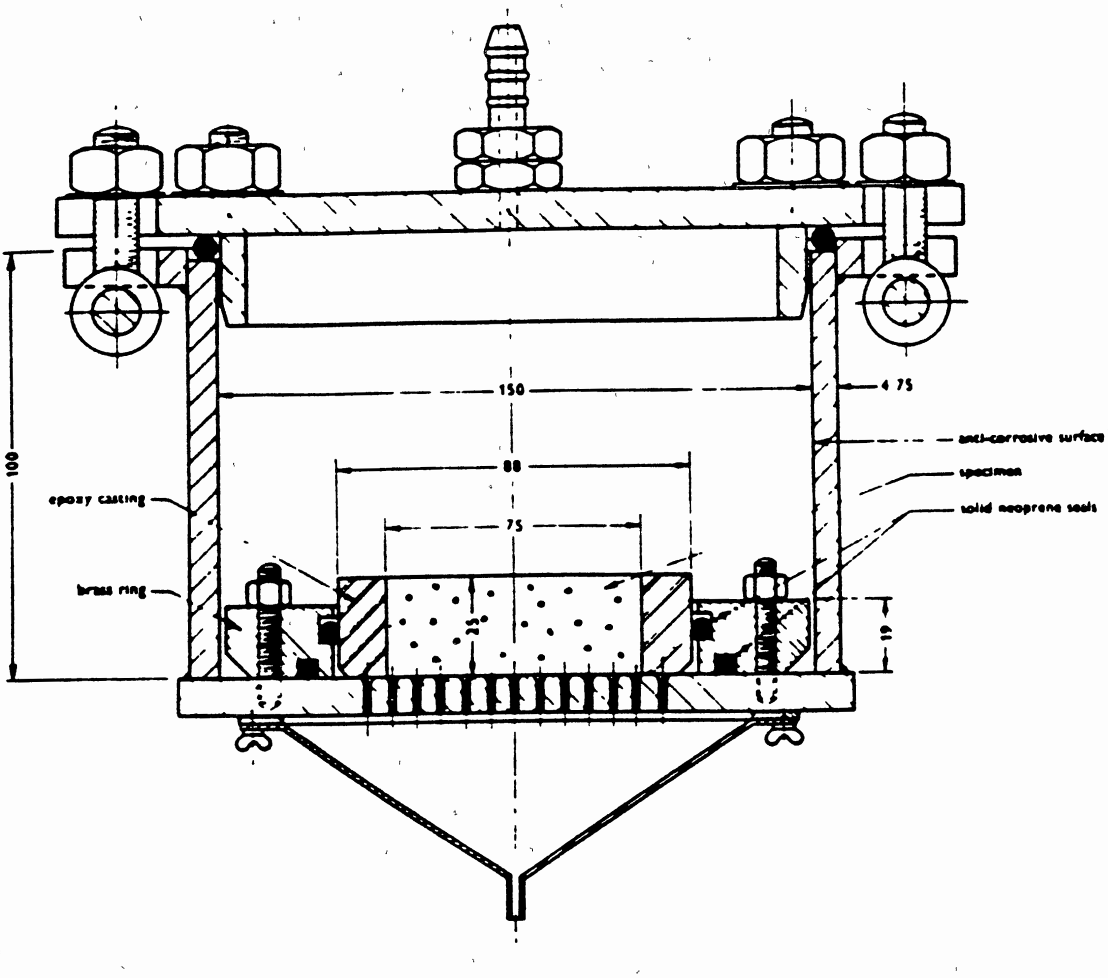

Figure 3. Section View of the Apparatus Developed by Meulen and Dijk [7]

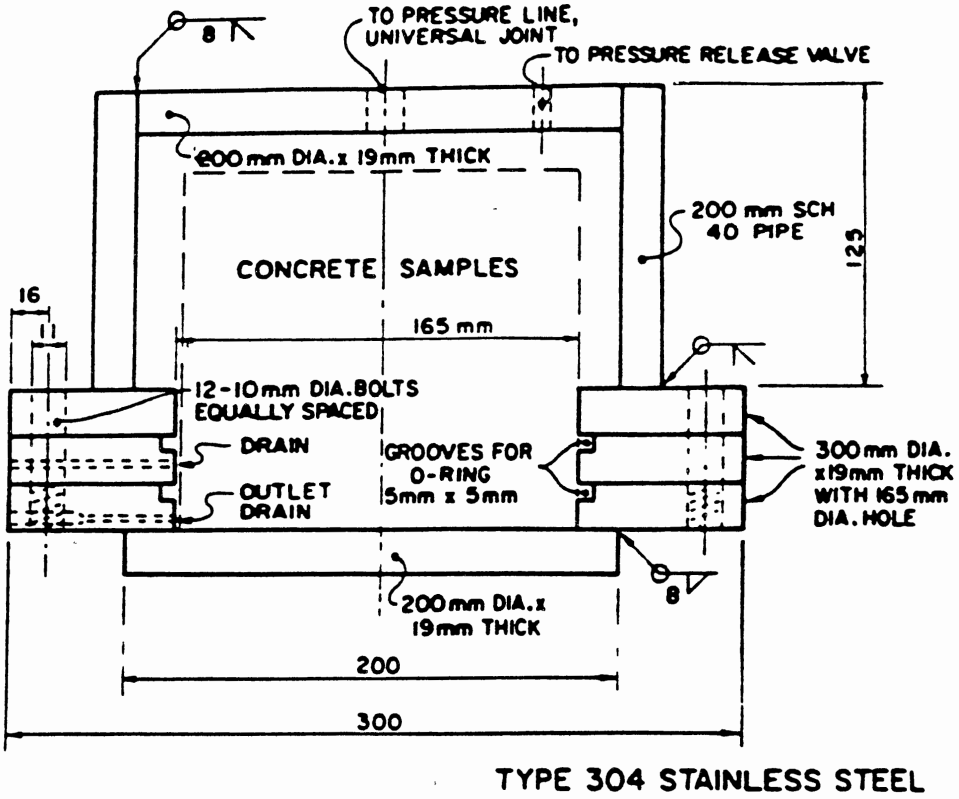

Figure 4. Section View of the Pressure Cell Developed by Hope and Malhotra [9]

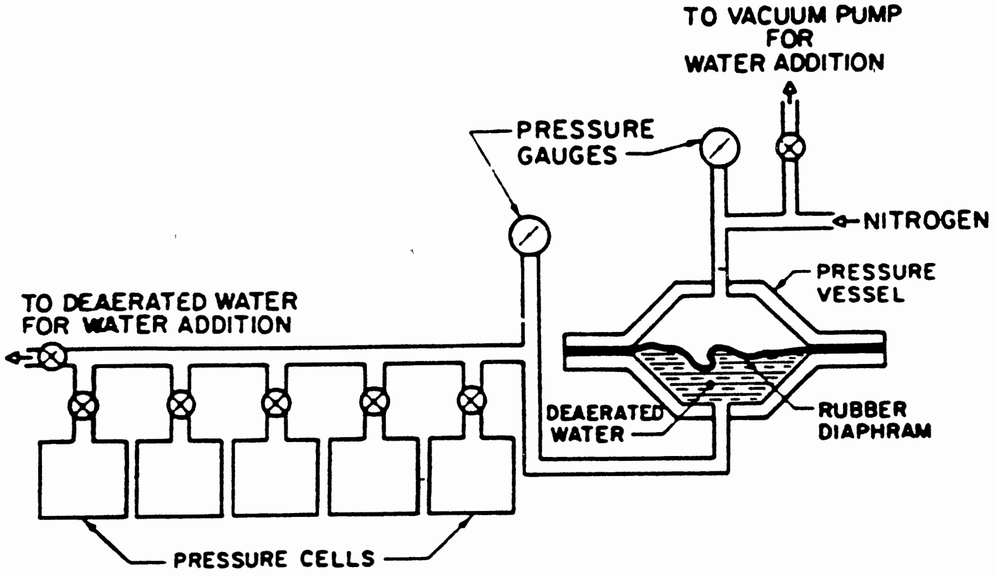

Figure 5. Schematic of the Apparatus Developed by Hope and Malhotra [9]

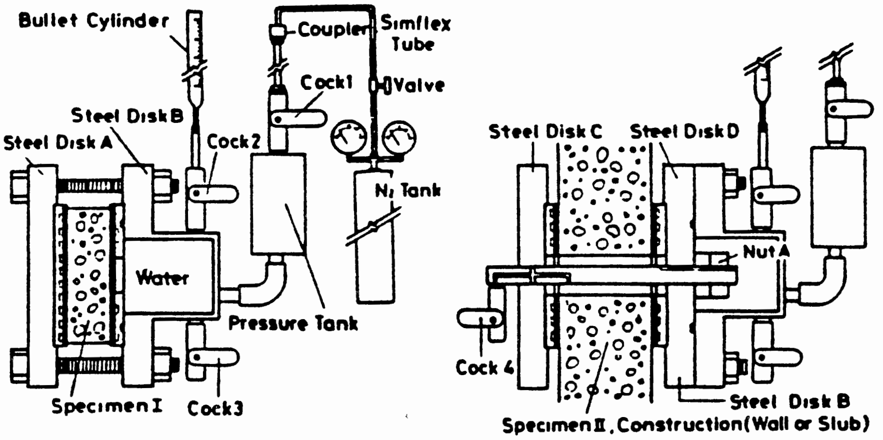

Figure 6. Schematic of the Apparatus Developed by Tanahashi et al [11]

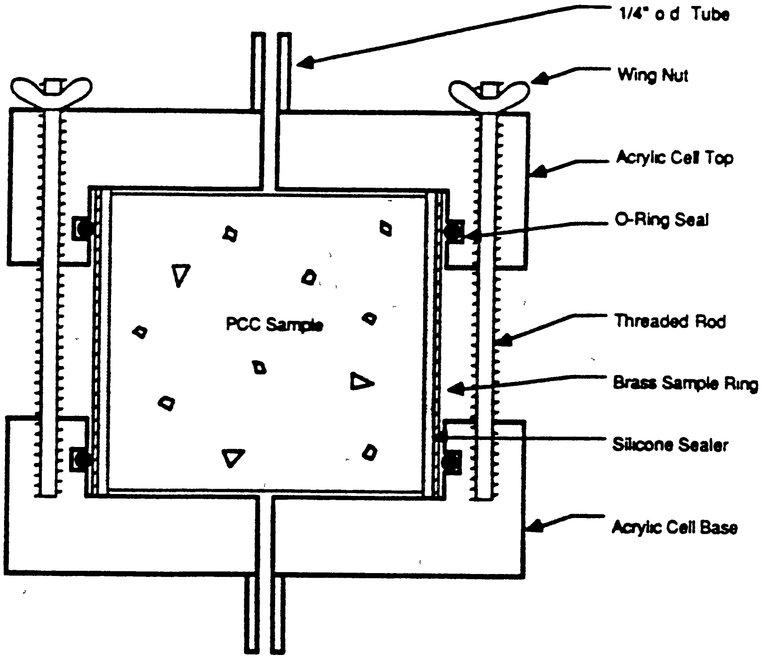

Figure 7. Section View of the Cell Developed by Janssen [12]

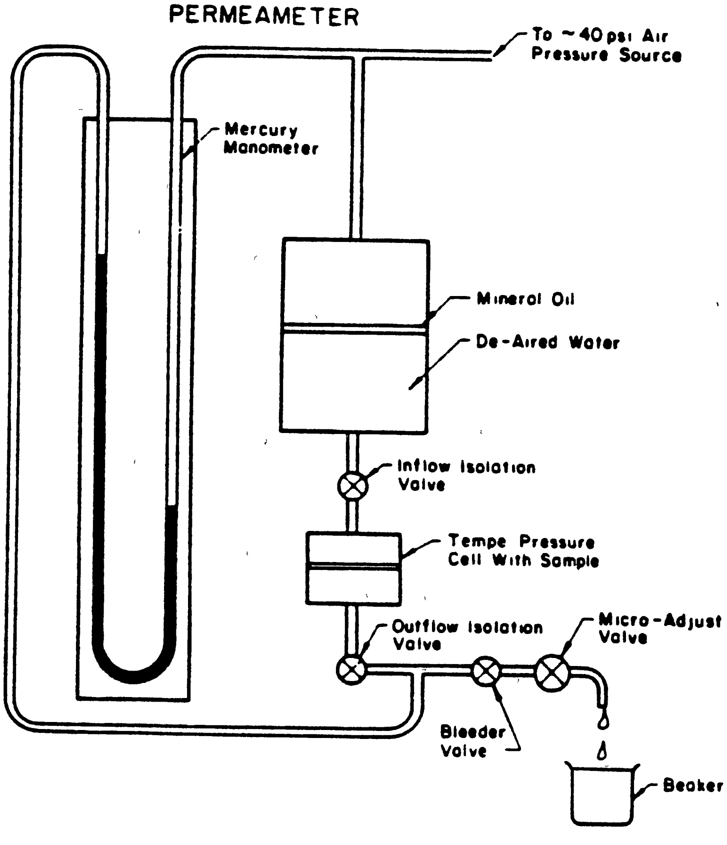

Figure 8. Schematic of the Apparatus Developed by Janssen [12]

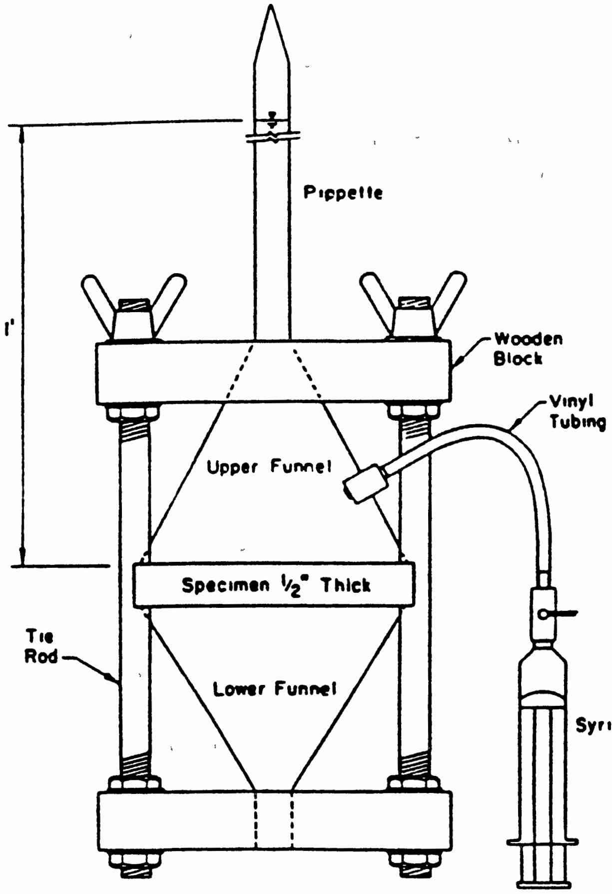

Figure 9. Schematic of the Apparatus A Developed by Ludirdja, Berger and Young [13]

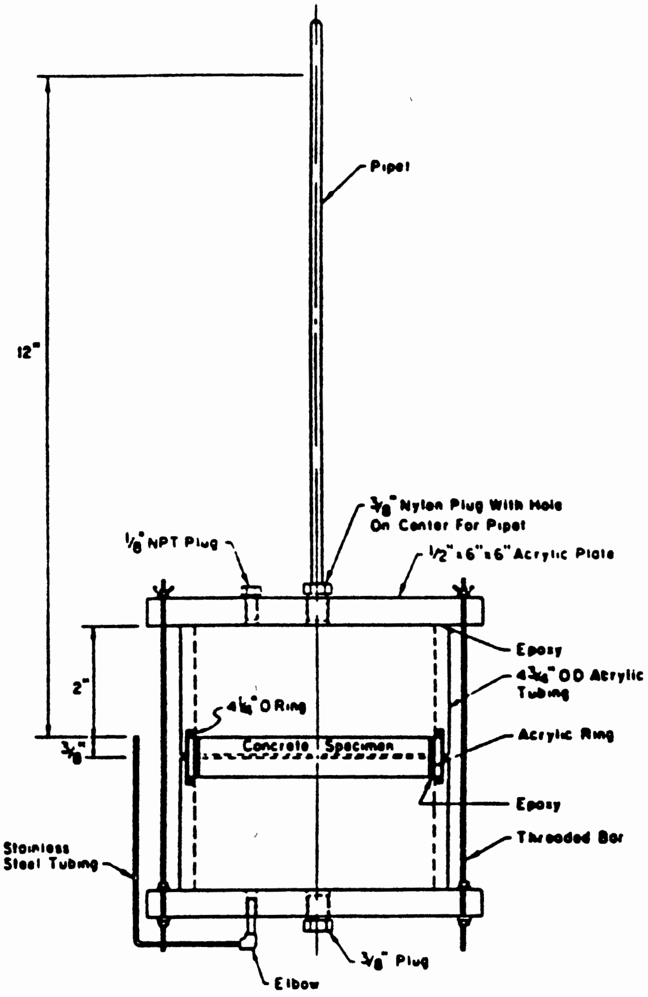

Figure 10. Schematic of the Apparatus B Developed by Ludirdja, Berger and Young [13]

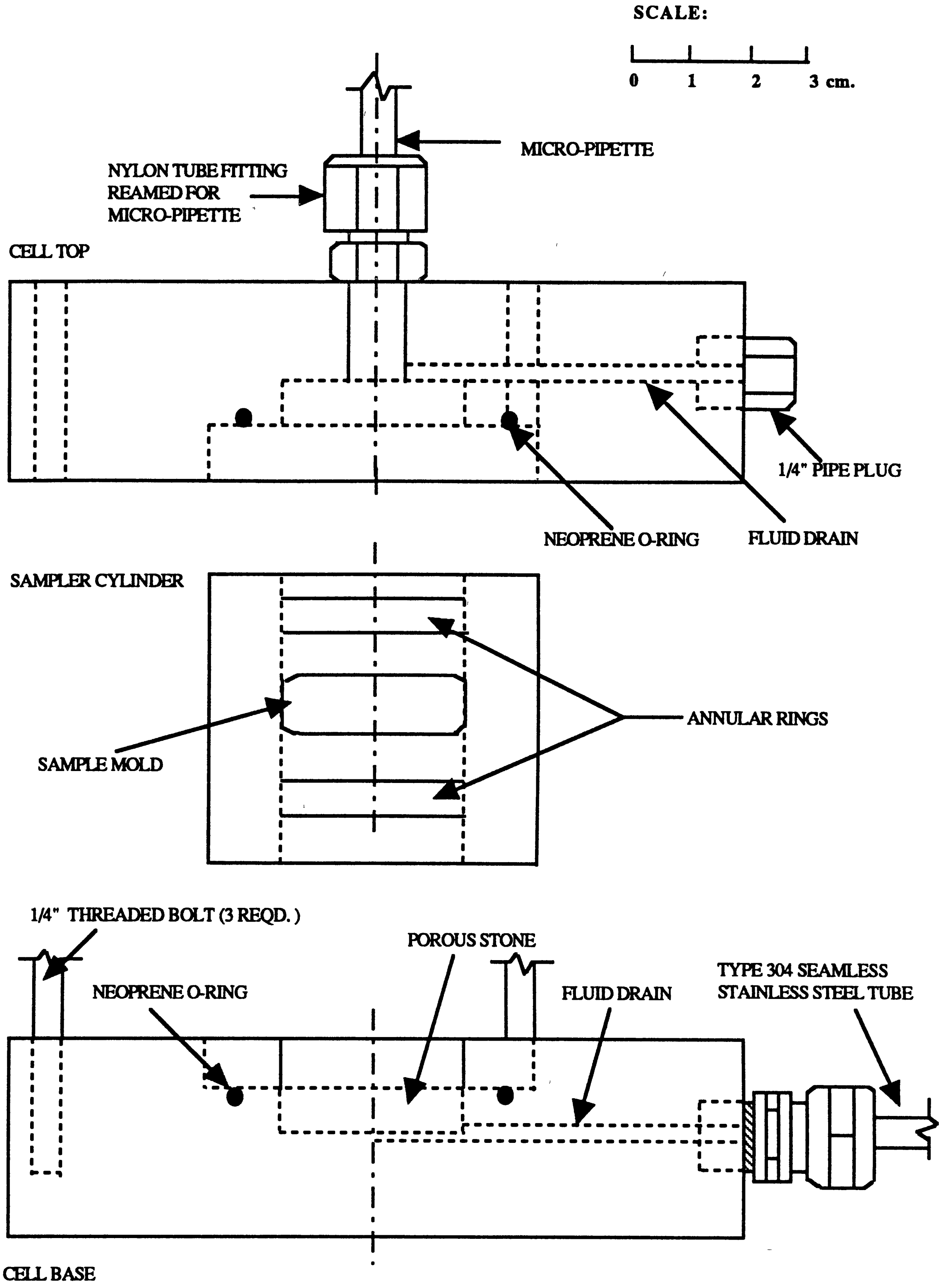

Figure 11. Construction of Permeability Cell

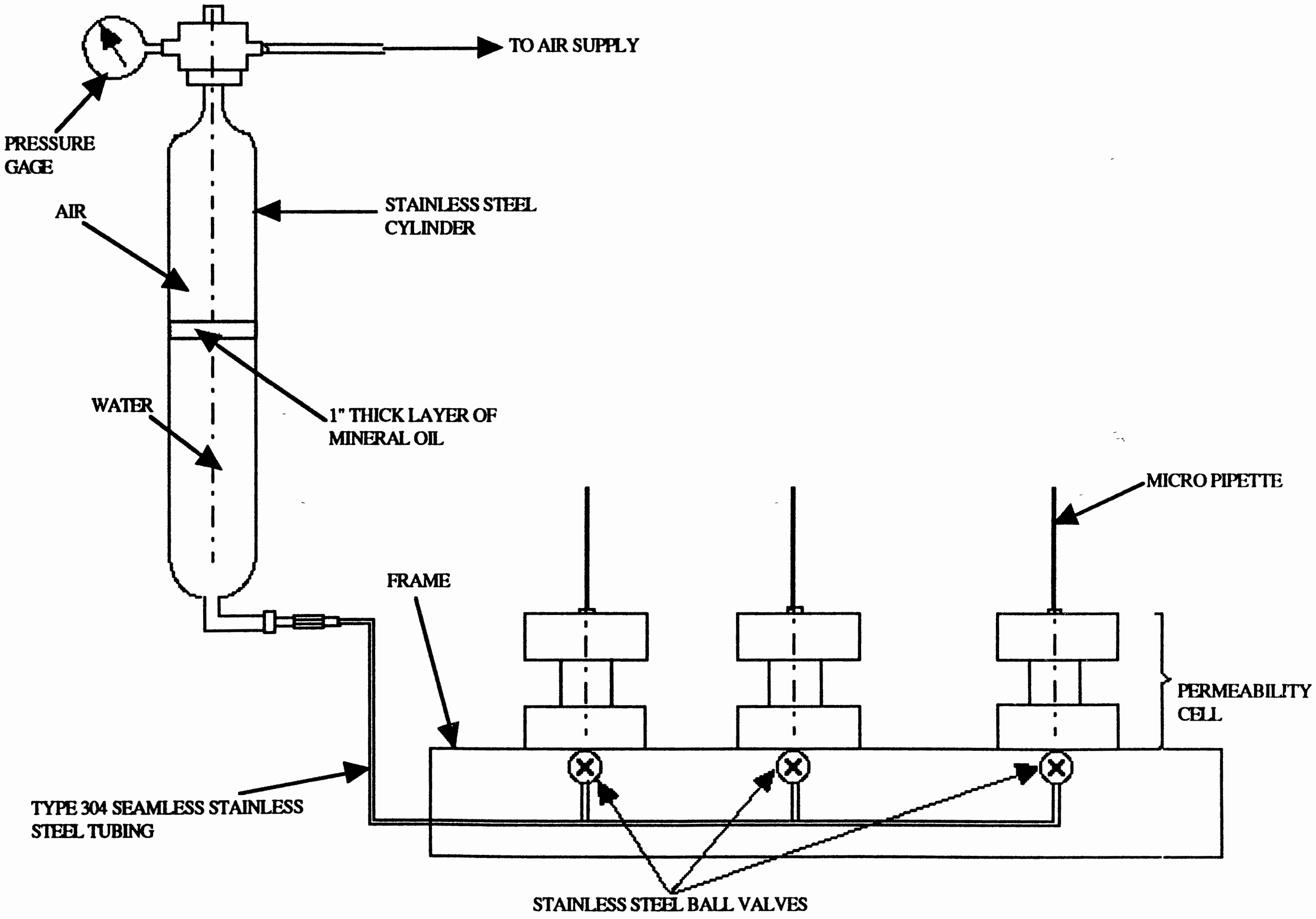

Figure 12. Schematic of the Permeability Apparatus

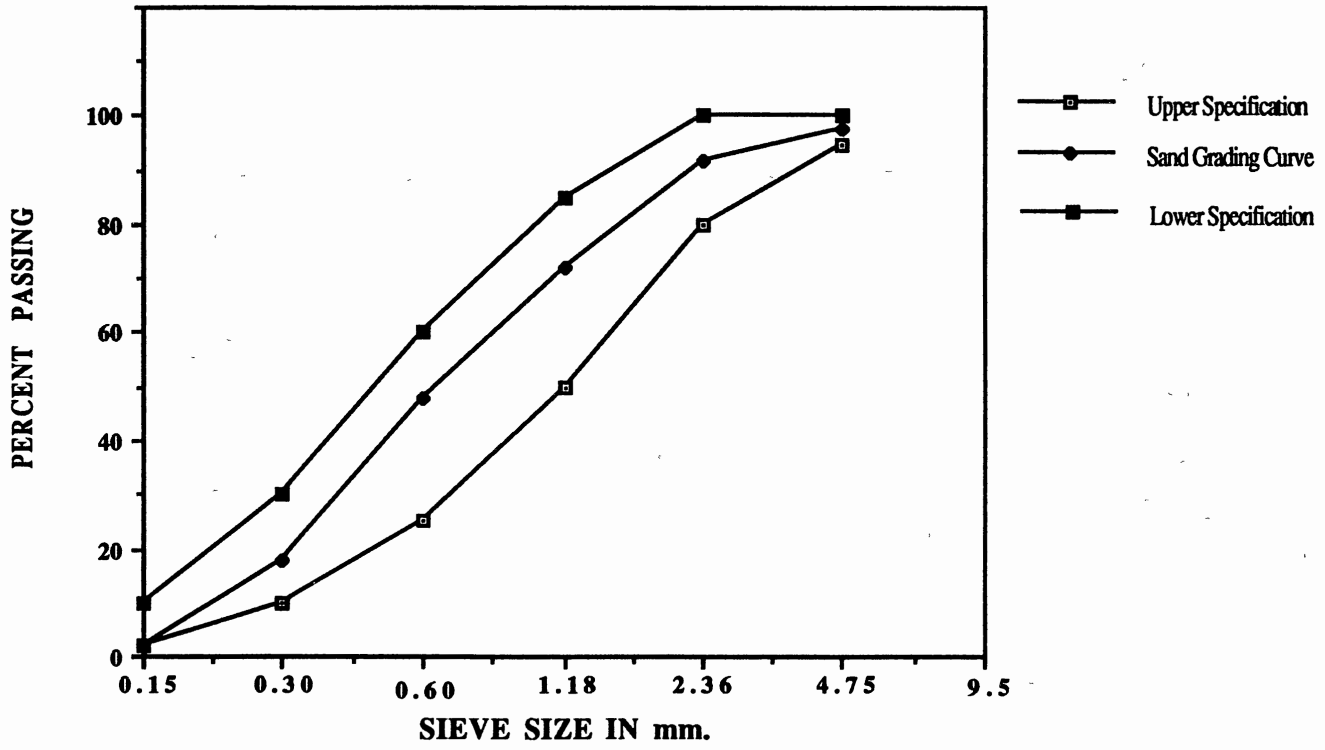

Figure 13. Grading Curve for Fine Aggregate

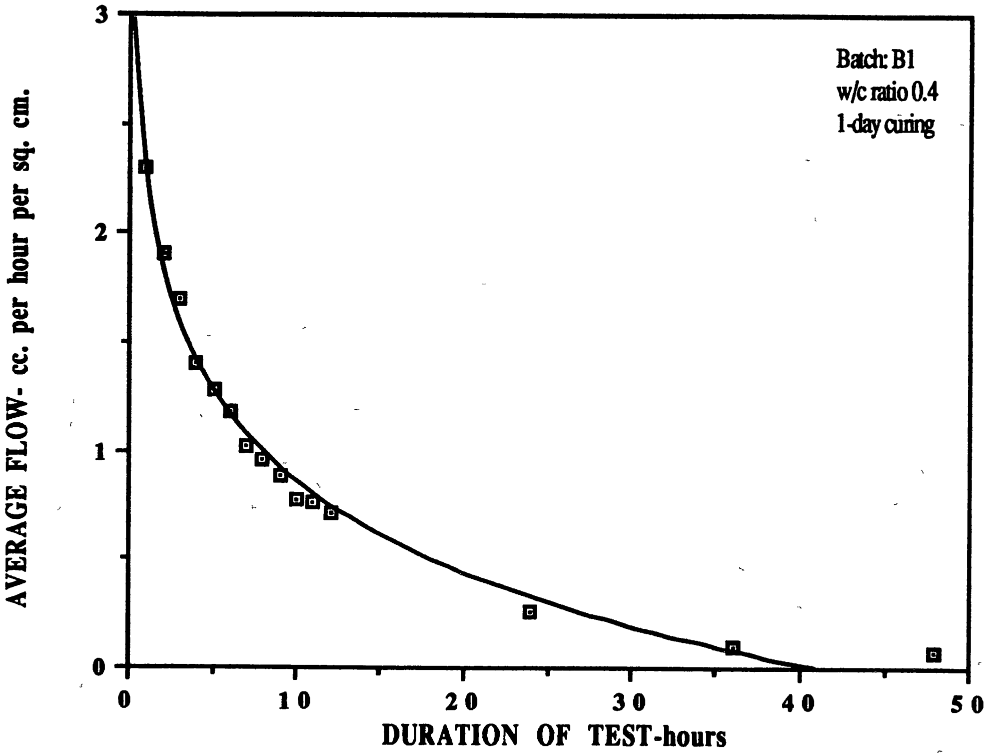

Figure 14. Average Flow- Duration of Test: Batch B1 w/c Ratio 0.4, 1-Day Cure

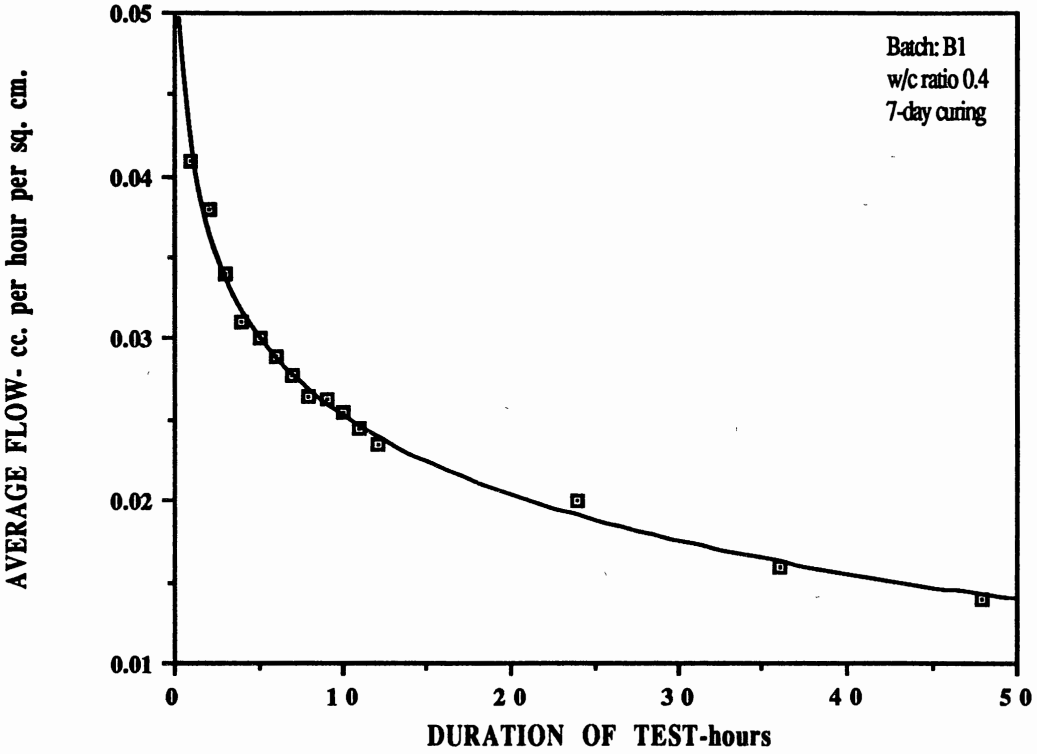

Figure 15. Average Flow-Duration of Test: Batch B1
w/c 0.4, 7-Day Cure

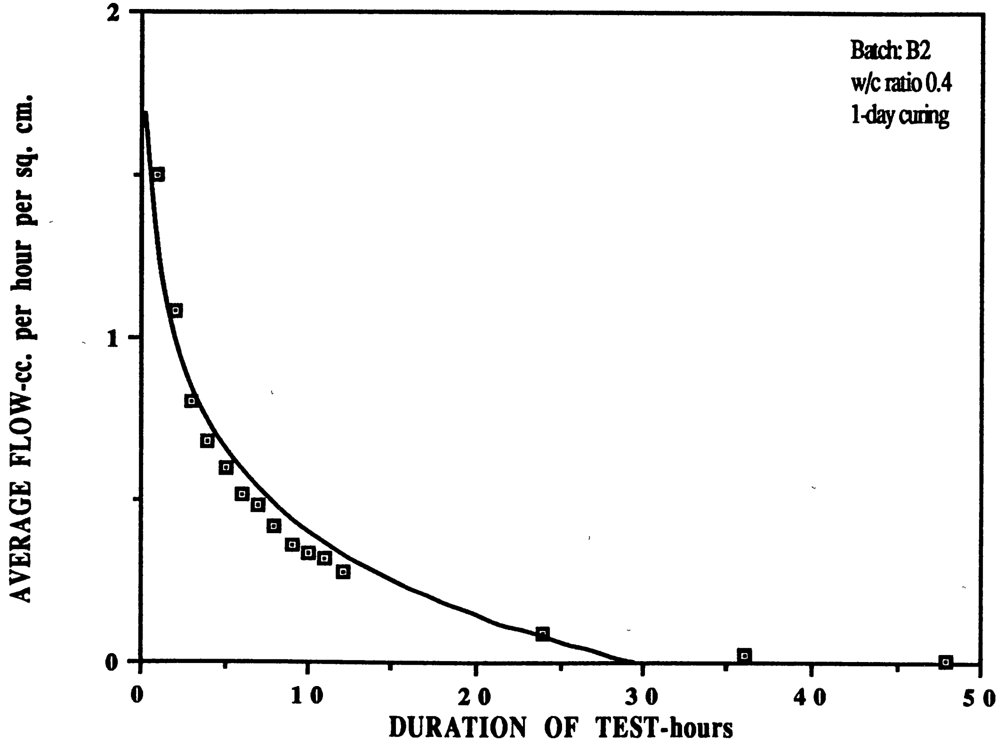

Figure 16. Average Flow-Duration of Test: Batch B2 w/c Ratio 0.4, 1-Day Cure

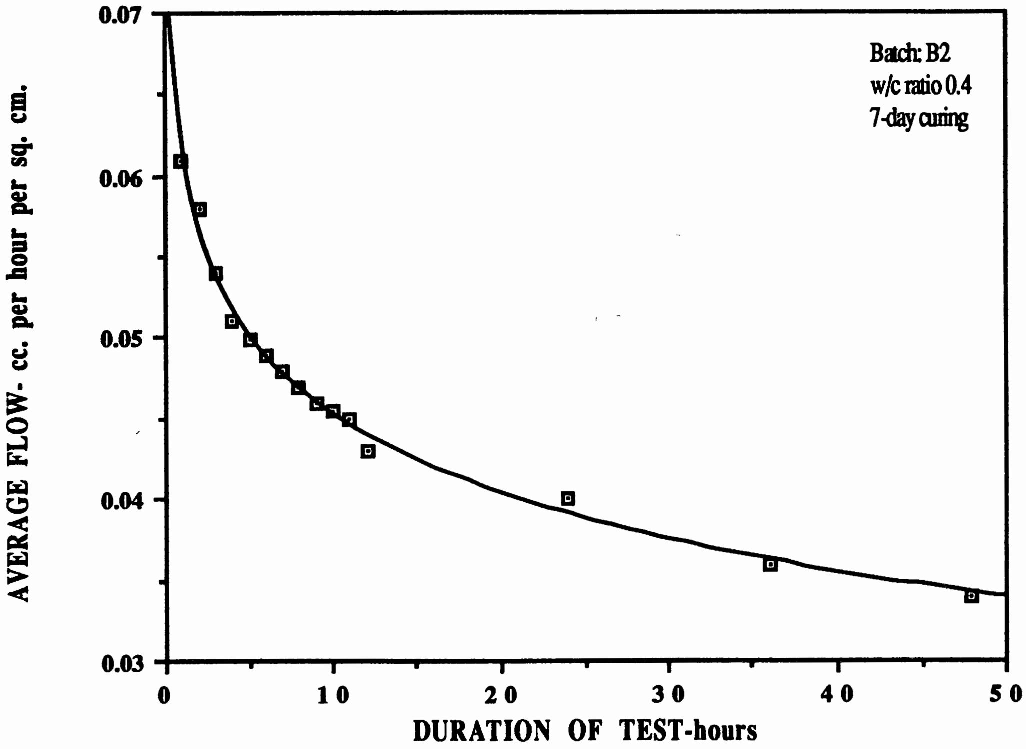

Figure 17. Average Flow-Duration of Test: Batch B2 w/c Ratio 0.4, 7-Day Cure

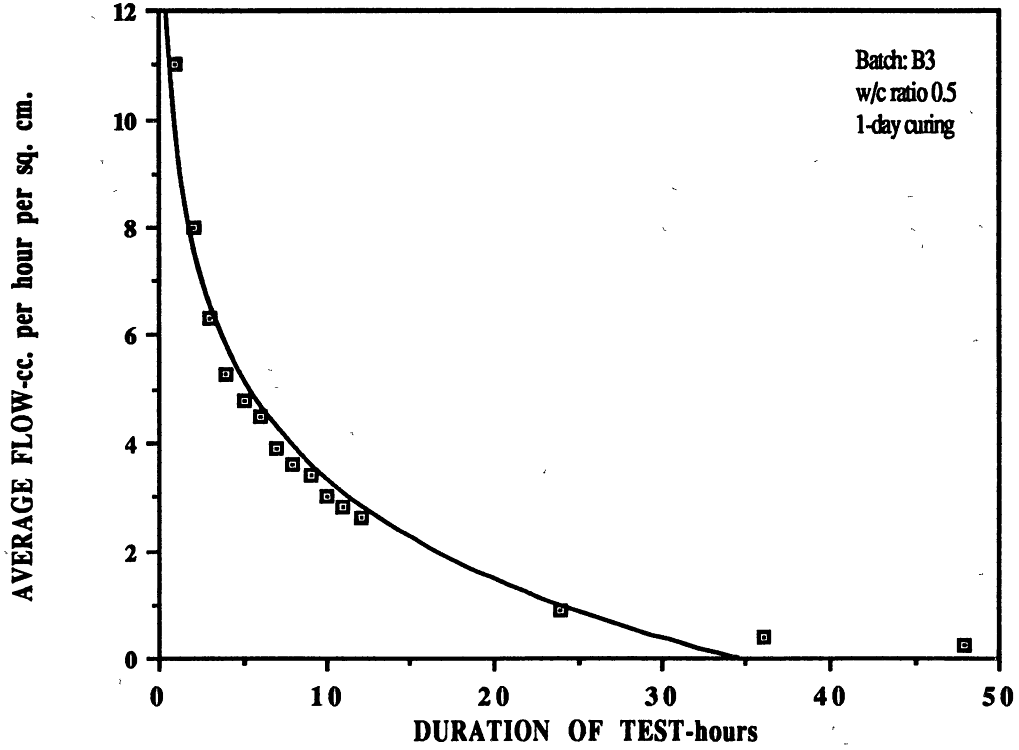

Figure 18. Average Flow- Duration of Test: Batch B3
w/c Ratio 0.5, 1-Day Cure

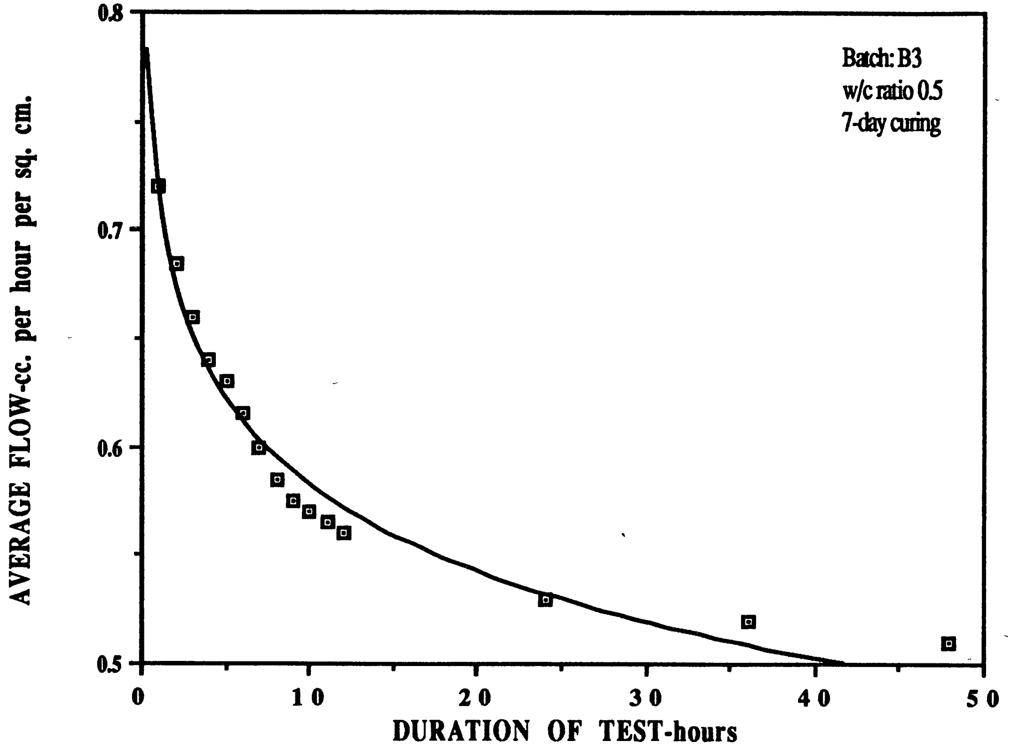

Figure 19. Average Flow- Duration of Test: Batch B3 w/c Ratio 0.5, 7-Day Cure

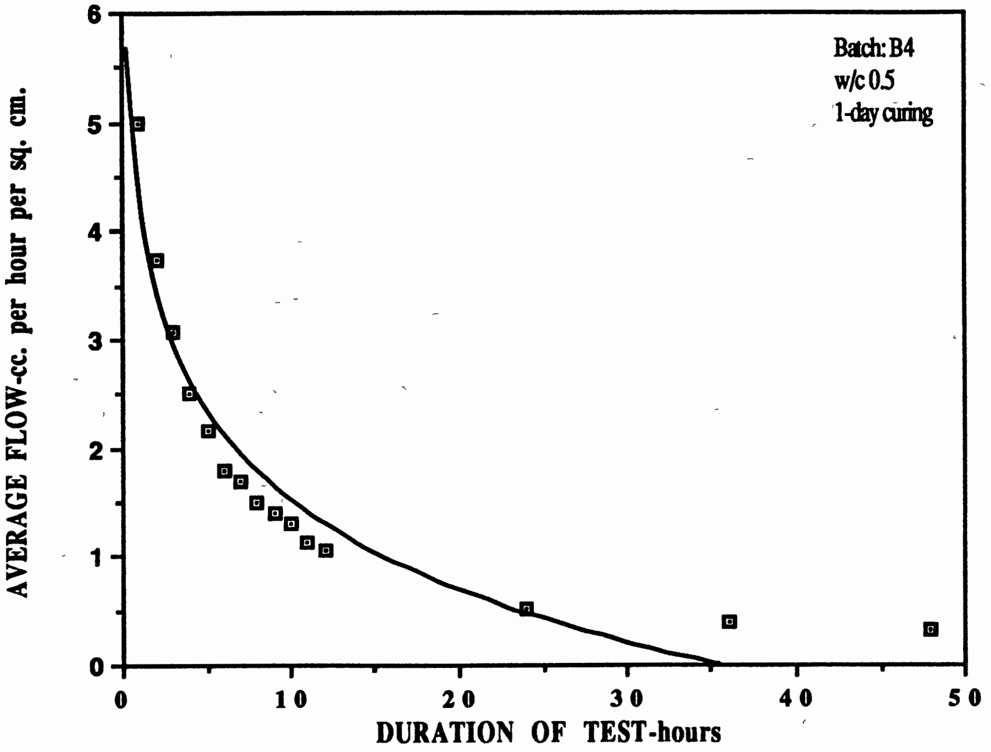

Figure 20. Average Flow- Duration of Test: Batch B4
w/c Ratio 0.5, 1-Day Cure

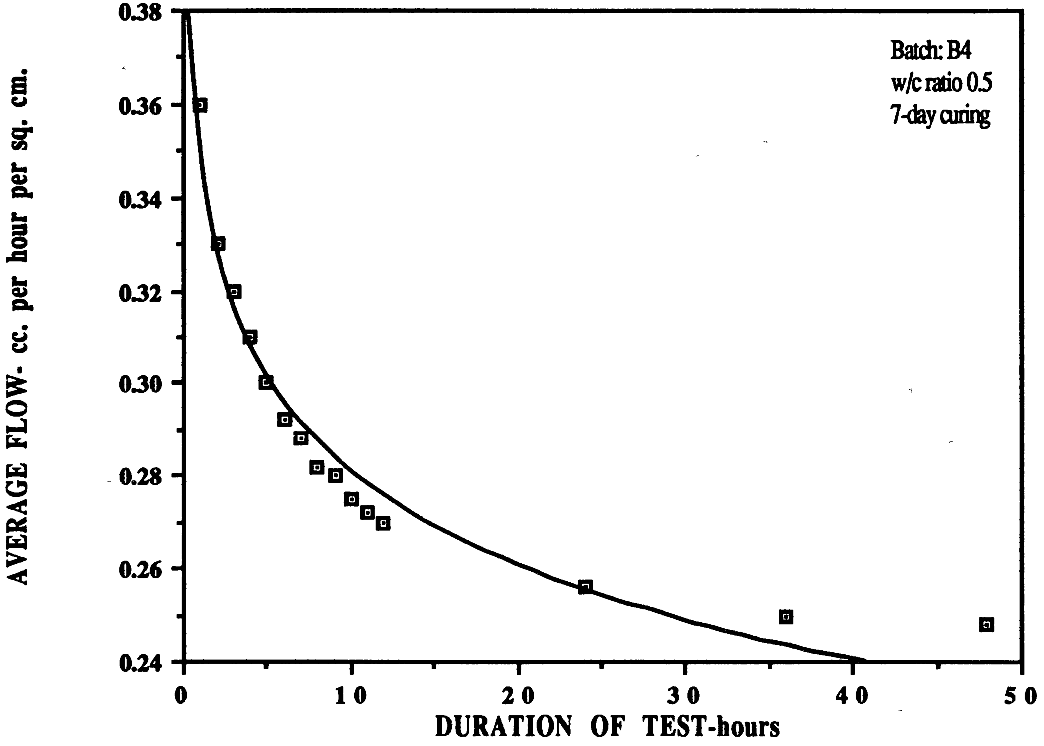

Figure 21. Average Flow- Duration of Test: Batch B4
w/c Ratio 0.5, 7-Day Cure

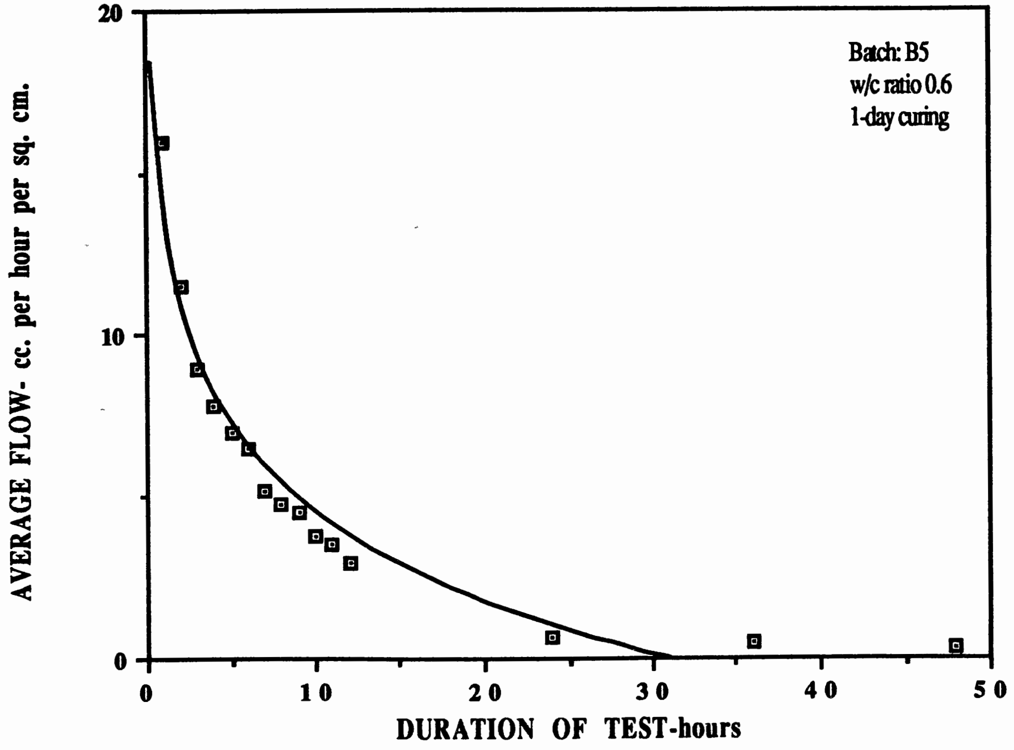

Figure 22. Average Flow-Duration of Test: Batch B5 w/c Ratio 0.6, 1-Day Cure

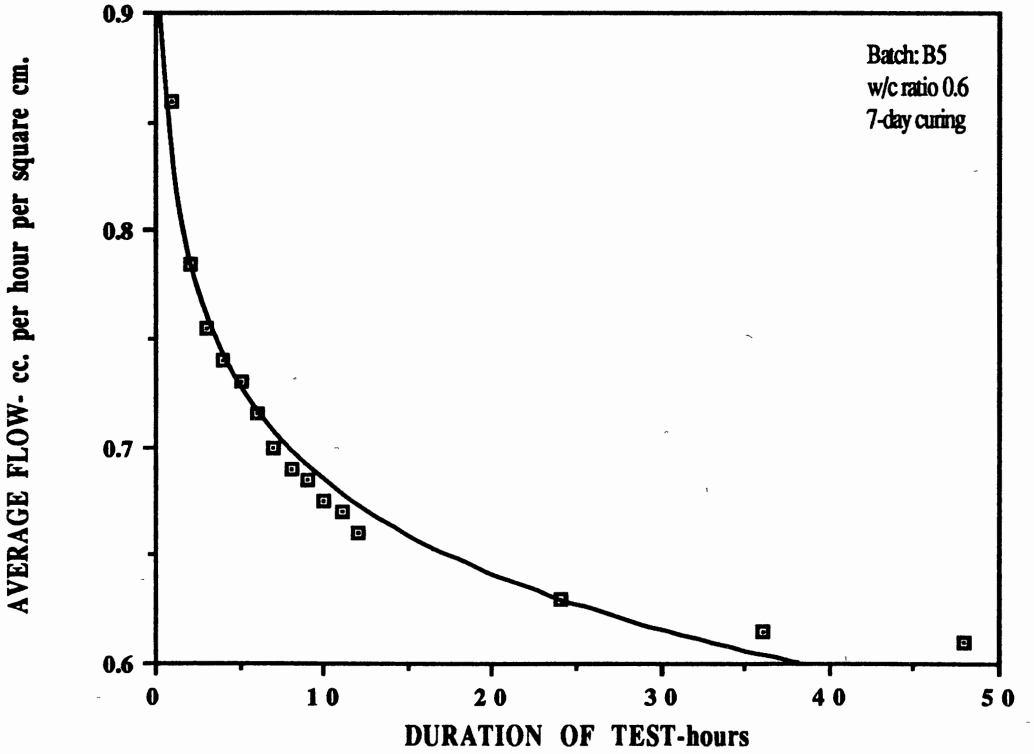

Figure 23. Average Flow-Duration of Test: Batch B5 w/c ratio 0.6, 7-Day Cure

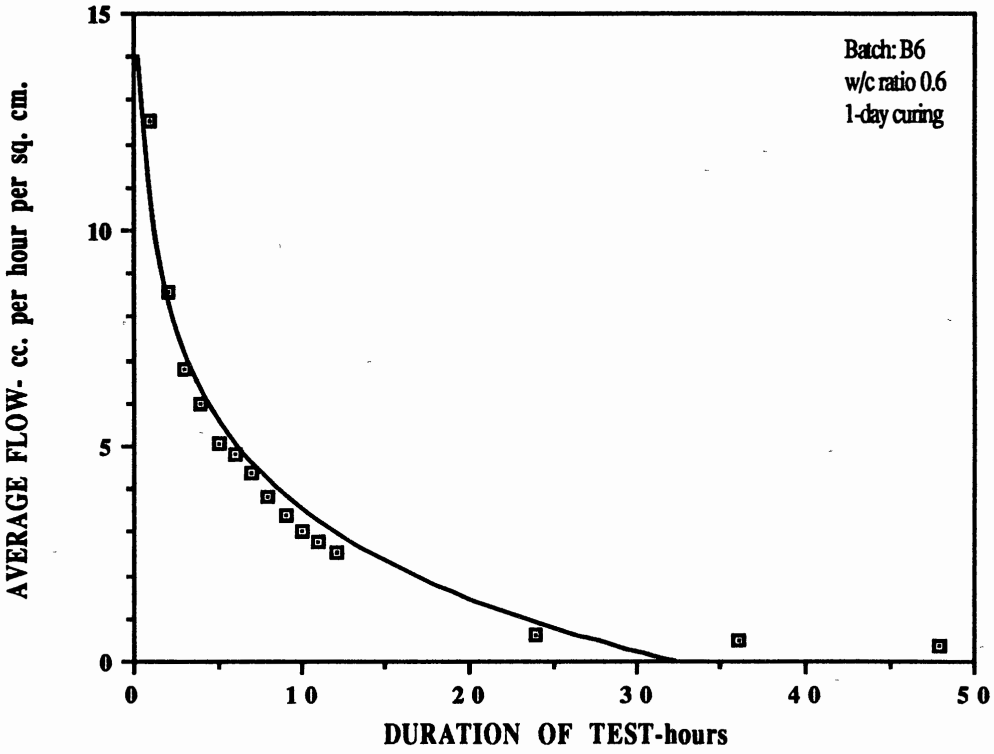

Figure 24. Average Flow-Duration of Test: Batch B6
w/c Ratio 0.6, 1-Day Cure

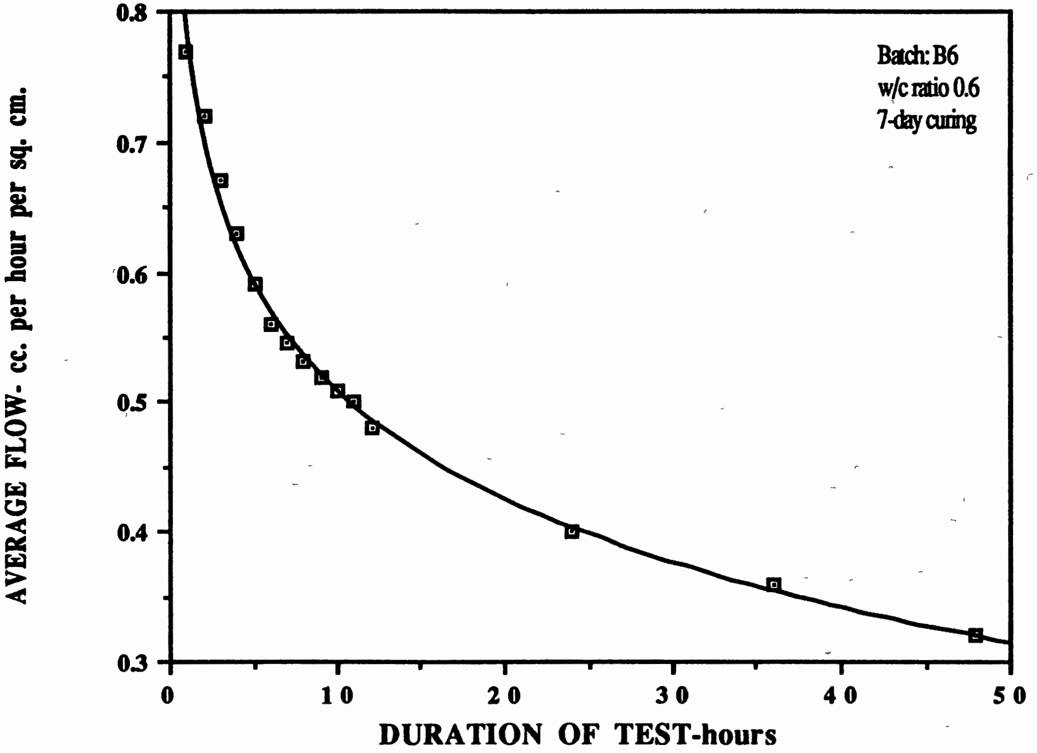

Figure 25. Average Flow-Duration of Test: Batch B6 w/c Ratio 0.6, 7-Day Cure

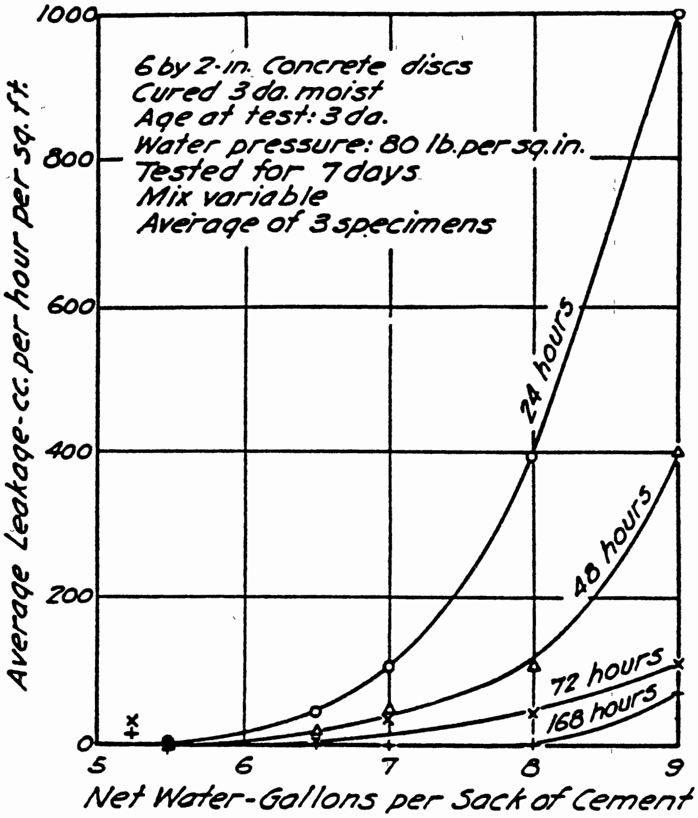

Figure 26. Average Leakage (Flow) for Different Periods of Test [1]

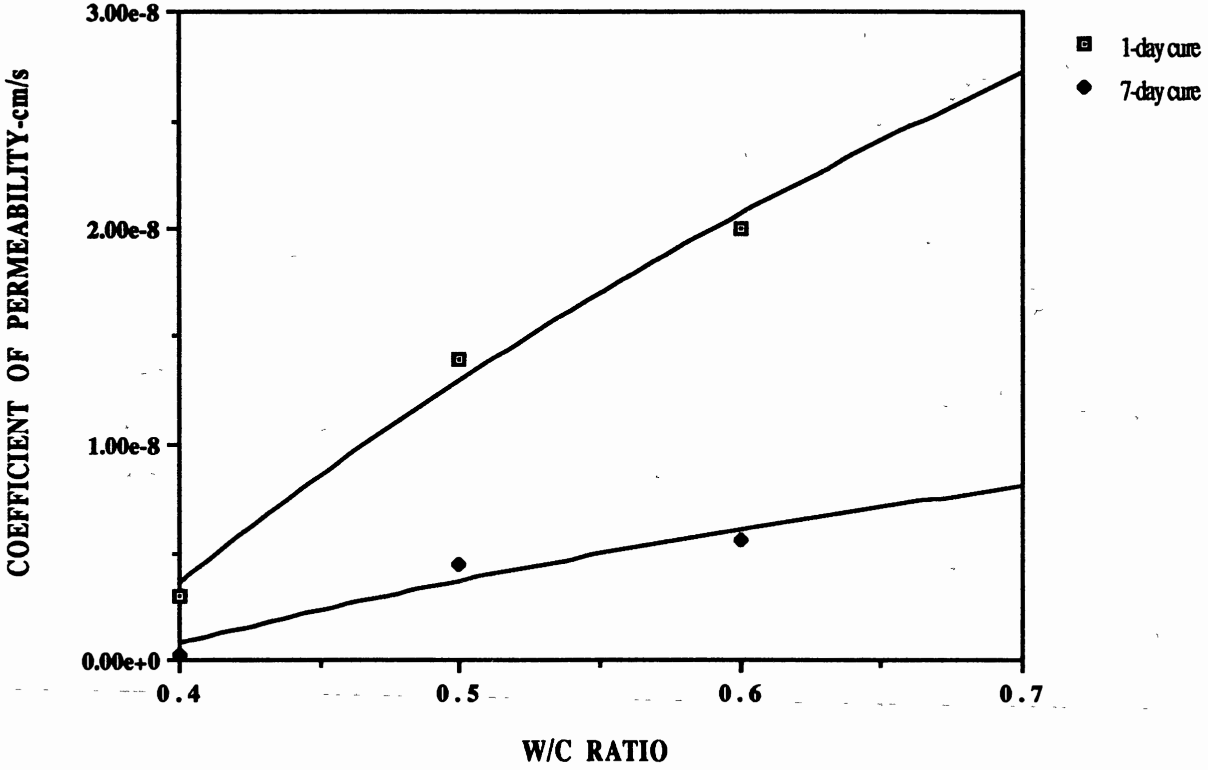

Figure 27. Coefficient of Permeability- Water-Cement Ratio

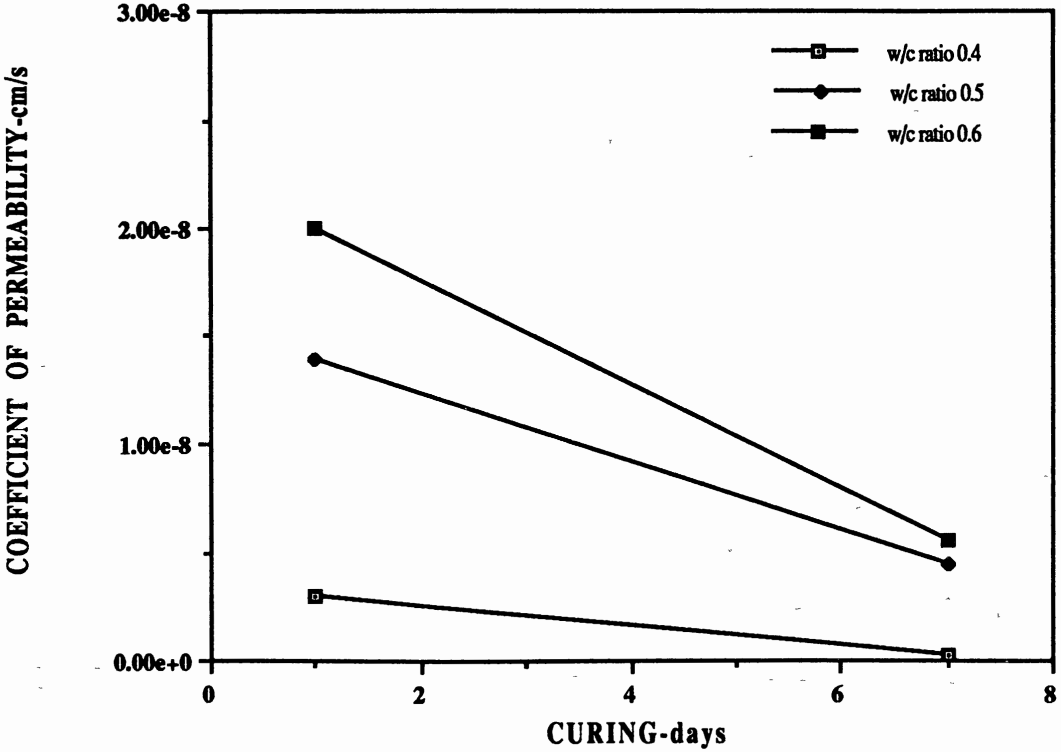

Figure 28. Coefficient of Permeability- Curing

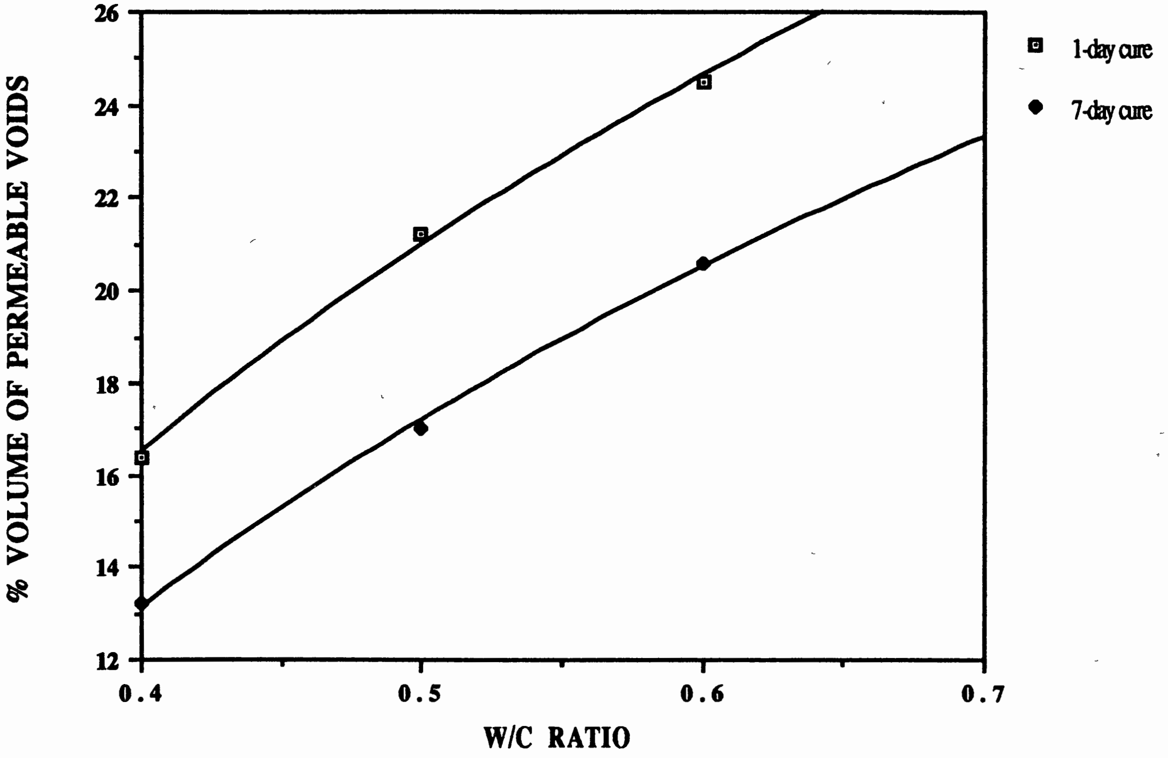

Figure 29. Percentage Volume of Permeable Voids- Water-Cement Ratio

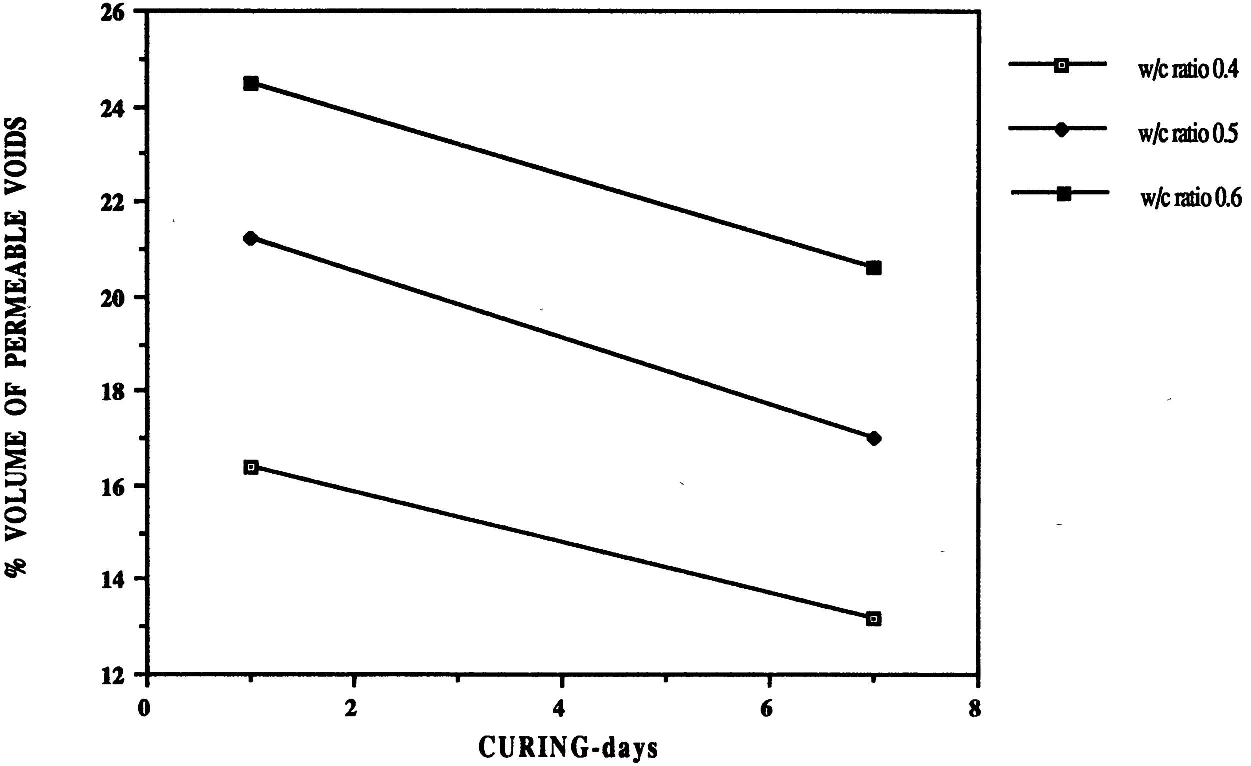

Figure 30. Percentage Volume of Permeable Voids-Curing

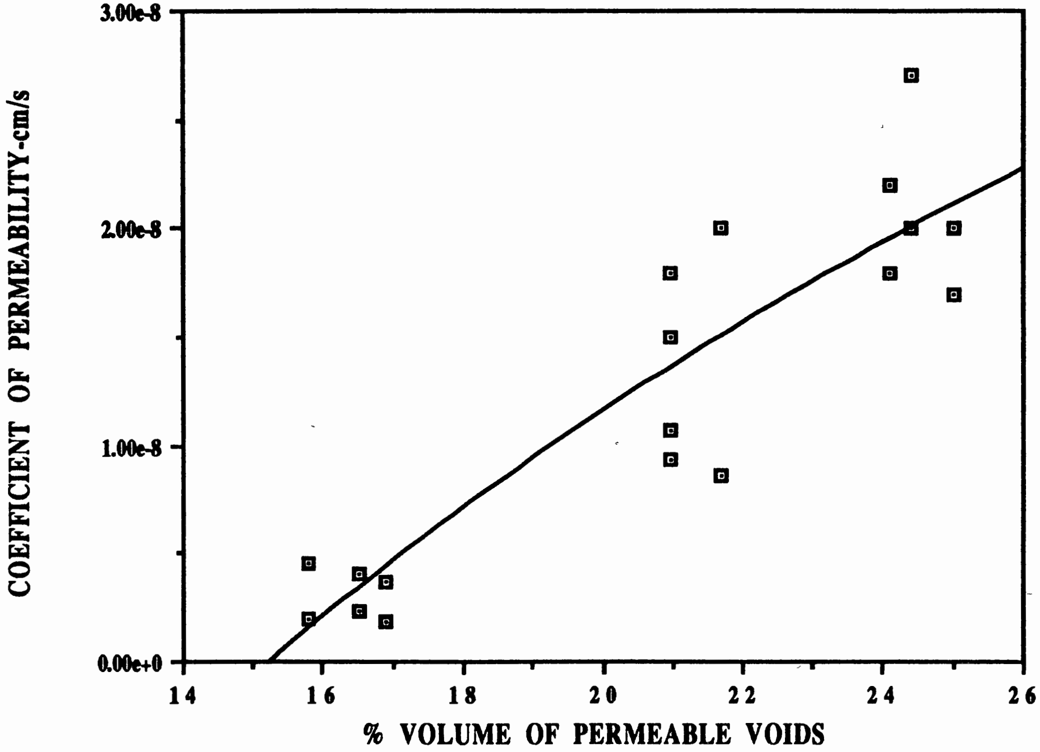

Figure 31. Volume of Permeable Voids- Coefficient of Permeability: 1-Day Cure

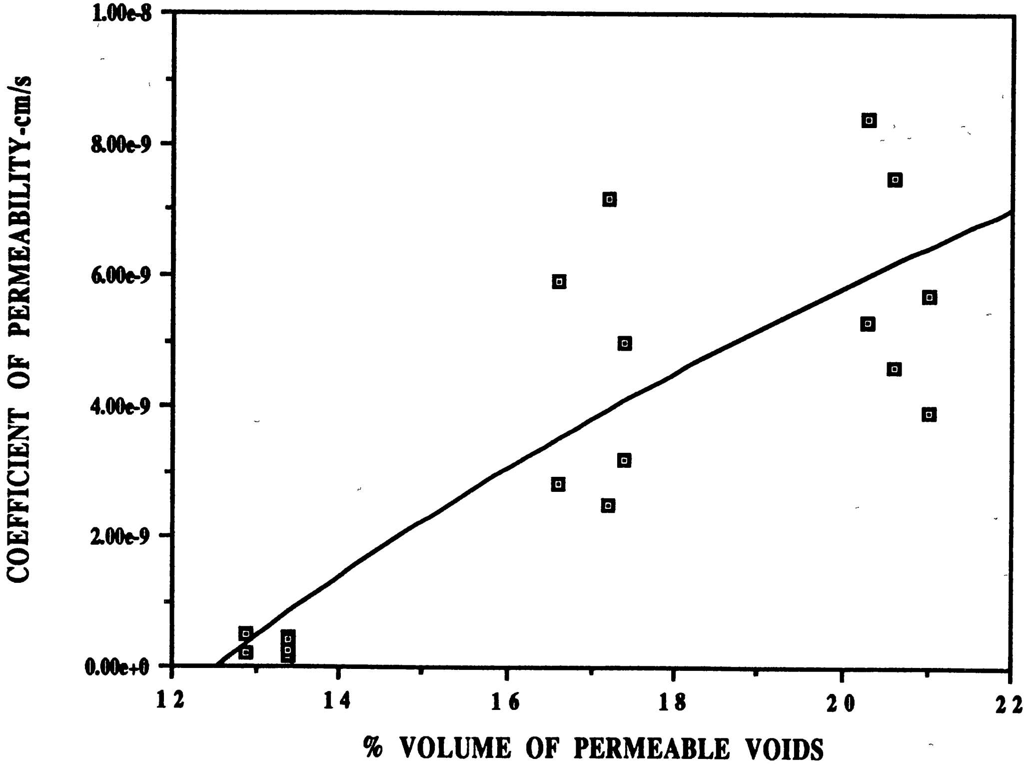

Figure 32. Volume of Permeable Voids- Coefficient of Permeability: 7-Day Cure

VITA 2

Zameer Ahmed

Candidate for the Degree of

Master of Science

Thesis: DEVELOPMENT OF CONSTANT HEAD PERMEABILITY APPARATUS FOR CEMENT MORTARS

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