EXPERIMENTAL MEASUREMENTS ON THE PERMEABILITY COEFFICIENT OF A CONCRETE SAMPLE UNDER LOW PRESSURE DIFFERENCES

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ABSTRACT

This paper presents preliminary experimental results on the measurement of the air permeability coefficient in a concrete sample that has been subjected to constant pressure differences of 5 and 10 Pa ($3.45 \times 10^{-2} - 6.90 \times 10^{-2}$ psi). This experimental model simulates indoor radon gas entry by advection. A reliable air permeability system was designed to perform laboratory measurements on concrete samples under controlled conditions. The experimental setup consisted of a PC-data acquisition and control system, proportional needle valves, highly accurate pressure transducers, and a commercial visual programming language software package. The concrete sample tested was approximately 4" in length, 3.5" in diameter, and of standard 1:2:4 (cement:sand:pea gravel) composition with a water-to-cement ratio of 0.5. A comparison between past and present air permeability coefficient results is presented. Details of the innovative experimental setup and procedures are described.

INTRODUCTION

Concrete is a porous material which easily allows radon gas to flow through it by the transport mechanisms of advection and diffusion. The permeability of concrete describes its ability to act as a barrier to gas movement when a pressure gradient exists across the concrete. For concrete with high permeability, pressure effects dominate diffusion effects resulting in radon gas advection as the major transport mechanism. There have been a number of studies pertaining to the advective flow of radon gas through concrete as well as the measurement of the permeability coefficient of air in concrete (Kendrick 1991; Nielson and Rogers 1991; Rogers and Nielson 1992; Scott 1993; Rogers et al. 1994; Snoddy 1994; Renken and Rosenberg 1995; Sanjuan and Munoz-Martialay 1995, 1996, 1997; Maas and Renken 1997).

However, there exists little experimental data on the permeability coefficient of air in concrete for low pressure differences. The majority of studies have documented permeability coefficients at differential pressures beyond the scope of advective radon entry problems in residential construction (i.e., Δp ~ 5 - 10 Pa). Permeability measurements under specified high pressure difference conditions have been found not to scale linearly to the small pressure differences of interest. This nonlinearity for large pressure differences normally leads to an underestimate of the flow velocity at low pressure difference conditions and hence, a large variance in the permeability value (Colle 1981). These previous experimental investigations have neglected to account for the *slip effect* found at low pressures when extrapolating values of K. If permeability measurements are made under conditions different (e.g., large applied pressures) from those for which they are to be applied (e.g., the representation of K at low differential pressures symbolic of radon gas entry), a correction factor has to be made. This correction is represented by the *slip effect* where the superficial gas permeability (i.e., the value of K in Darcy's law) is a linear function of the inverse mean pressure of the gas. Since the cause of this dependence is gas slippage, it increases with increasing free path length (Sheidegger 1974).

This paper reports the findings of a design project with an objective of measuring concrete air permeability coefficients at very low pressure differences that simulate radon entry condition in residential construction. An original experimental system, which utilizes control technology and state-of-the-art instrumentation to measure the permeability of concrete samples, was designed and utilized. The resulting system allows accurate measurements of the concrete air permeability coefficient at differential pressures as low as 5 Pa (3.45 x 10^{-2} psi).

EXPERIMENT

Concrete Samples

The concrete sample used in this investigation simulated standard poured-concrete for basement foundations (Hool 1918; USBR 1938). The ingredients for this concrete were cement, sand, stones, and water. Pea gravel was used to obtain a homogeneous mix with respect to the size of the sample. A water-to-cement ratio, w/c of 0.5 was used and the ratio of the concrete ingredients was 1:2:4 (cement:sand:pea gravel). A cylindrical aluminum holder was employed to cast and hold the concrete sample. The sample was 4.2" in thickness and 3.5" in diameter. The concrete was removed from the holder 24 hours after casting and placed in a high humidity chamber for 30 days as per ASTM specifications (ASTM 1994). After curing, the sample was allowed to dry at ambient conditions for one week. The sample was then placed back into the cylindrical holder and the entire circumference was sealed with a laboratory-proven cementitious epoxy (Daoud 1998). Figure 1 is a photo of the example concrete sample in an aluminum holder.

Concrete Porosity

The physical characteristic of the concrete sample most important in the measurement of permeability is the porosity. Figure 2 is a schematic of the experimental system used to measure the porosity of the concrete sample. A gas expansion method as described by Maas and Renken (1997) was used to calculate the pore volume. This method employs the *Conservation of Mass*

and the *Boyle-Marriotte Gas Law* (Balmer 1990) to calculate the solid volume of the concrete sample. This solid concrete volume is determined by placing the concrete sample in the sample chamber of known volume. This chamber is then pressurized and allowed to come to equilibrium conditions. The chamber is then opened to the secondary "exhaust" chamber and again allowed to come to equilibrium. By using the *Boyle-Marriotte Gas Law* for constant temperature conditions, a mass balance states that the mass of air present before and after expansion of the sample chamber volume is the same. By simple algebraic manipulation, the volume of solid concrete in the sample is solved for and the percent porosity of the concrete can be calculated. Details can be found in Daoud (1998). This concrete sample had a porosity, ε = 10.3% with an overall experimental uncertainty of 3%.

Permeability Apparatus
Figure 3 is a photo of the experimental apparatus used to measure the permeability of air in concrete. More specifically, Fig. 4 provides a schematic diagram of the flow system. Here, the concrete sample in the aluminum holder is firmly bolted between the high and low pressure cylindrical chambers which are constructed of aluminum. Two identical mini proportional flow control valves with an orifice size of 0.032" are utilized to maintain a constant pressure difference across the concrete sample. These *needle* control valves are employed because of their ability to control small flows of air. Highly sensitive and accurate pressure transducers, thermistors, and relative humidity sensors measure pressure, temperature and humidity levels, respectively within the chambers. All of the sensors as well as the proportional control valves are connected to a modern PC-data acquisition and control system. (PC-DACS).

PC-DACS
The PC-DACS hardware consists of a personal computer (with a Pentium II processor operating at 200 MHz, with 32 MB RAM, a 4 GB hard drive, a color VGA monitor operating under the Windows98 platform) and an external cardcage that contained two different cards: a digital-to-analog (D/A) converter and a 32-channel scanning A/D converter. The PC-DACS monitors conditions (e.g., pressure, temperature, relative humidity) and electronically controls the operation of the two proportional control valves via a visual programming language (HP VEE 5.0). The software package handles measurements, instrument control, as well as data collection and processing. The programming language provides a set of powerful objects that can be connected to create a program, as opposed to having icons for every single programming function. Its instrument manager scans the bus for devices and automatically handles the interfacing details (e.g., address strings, drivers, management of I/O sessions). The software also allows the user to create operator interfaces, including soft front panels for instruments to visually represent data. Figure 5 is a flow chart of the HP VEE code used in our measurements. Two items in this flow chart that are expanded to show the internal functions are the WRITE DATA and CONTROL OF VALVES icons. These user objects are displayed in Figs. 6 and 7.

Process Summary
In summary, the automated process of how the setup works is as follows. The user inputs a prescribed pressure difference across the concrete sample when prompted by the program. The program automatically determines a variable range of pressure difference around the desired

differential pressure (e.g., ± 0.1 Pa). For example, if the user inputs 10 Pa as the desired Δp, the upper range will be 10.1 Pa with a lower range of 9.9 Pa. The program continues and measures pressures, temperatures as well as relative humidity levels. If the Δp across the concrete is above the 10.1 Pa level (as measured by the differential pressure transducer and the 32-channel scanning A/D converter card), the proportional flow control valve on the bleed-off of the high pressure chamber will open via a voltage increase and the inlet proportional flow control valve will close via a voltage decrease from the D/A converter card. If the Δp is below the 9.9 Pa level, the proportional flow control valve on the bleed-off of the high pressure chamber will close via a voltage decrease and the inlet proportional flow control valve will open via a voltage increase. If the designated differential pressure range is held (e.g., 9.9 Pa < Δp <10.1 Pa), the proportional control valves stay in their respective positions. The constant scanning of data acquisition channels and forwarding of electrical signals produces a steady-state pressure difference across the concrete sample so that the air permeability coefficient can be measured. The sensor channels can scan at a rate of 1000 times per second so that the proportional flow control valve can instantaneously adjust differential pressure conditions.

Permeability Coefficient
The permeability coefficient, K is the transport coefficient for permeability, and is the proportionality constant in Darcy's law that relates fluid flux through a porous material (concrete) to the pressure gradient:

$$Q = -\frac{K A \Delta p}{\mu L} \qquad (1)$$

where,

Q = volumetric flow rate of the fluid
K = permeability coefficient
A = cross-sectional area permeated
Δp = pressure difference across the porous medium (concrete)
μ = viscosity of the permeating fluid
L = length of porous medium.

Darcy's law in this form is valid for sufficiently slow, unidirectional, steady-state flow in the direction of the length of the samples. The permeability coefficient "factors in" the combining dynamics of physical properties of the porous medium and the permeating fluid. The volumetric gas flow rate was calculated from the ideal gas law and the molecular volume of air with the measured pressure increase, temperature, and volume of the low pressure chamber during the test (Maas 1997).

$$Q = mv_{air} \frac{\Delta n}{\Delta t} = mv_{air} \frac{P_i V}{RT \Delta t} \qquad (2)$$

where,

mv_{air} = molecular volume of air
Δn = mass increase in low pressure chamber
Δt = unit of time over which the pressure and mass increase
P_i = pressure increase in the low pressure chamber
V = volume of low pressure chamber
R = gas constant
T = temperature in low pressure chamber

Complete details of the experimental setup and procedures can be found in Abraham (1999).

RESULTS

Table 1 reports the measured concrete air permeability coefficients for the two prescribed pressure differences utilizing the experimental system described. More specifically, the measured values of K ranged between 5.67×10^{-11} cm^2 and 6.02×10^{-11} cm^2 for applied pressure differences of 5 and 10 Pa, respectively. These values of K translate into a 5.82% difference when the Δp is reduced by 50% at these low pressures. The experimental uncertainty of the measured permeability coefficient is estimated to be approximately ±5%.

Table 1 also presents a comparison between the present preliminary experimental results with experimental data from other investigations. Here, information on the porosity and the water-to-cement ratio of the tested concrete as well as the pressure difference that was used to measure the value of K are listed for each study. Porosity is not the only factor related to concrete air permeability. The degree of hydration, hence permeability is dependent on the water-to-cement ratio. the type of cement used. age and environment of the concrete. While it is difficult to directly compare these results due to the many different types of concretes that were tested. the permeability coefficient seems to follow the same trend as the porosity for similar w/c ratios (i.e., an increase in porosity generates larger values of K).

As indicated, almost all of the previous studies have used pressure differences across the concrete that were 10^3 - 10^5 times greater in order of magnitude than the present work. The result is values of K for similar porosity and w/c ratios that are at least an order of magnitude less in value than those reported here. The wide range of measurements suggests that the different pressure applications may affect the air permeability in concrete.

CONCLUSIONS AND RECOMMENDATIONS

An innovative laboratory apparatus to accurately measure the concrete air permeability at low pressure differences that simulate indoor radon gas entry by advection has been described. The main components of the system are proportional flow control valves and sensitive pressure

transducers that work in combination with a PC-data acquisition and control system. Preliminary experimental results show that measurements of permeability may be affected by the applied pressure difference across the concrete. Because previous investigations have used higher differential pressures to calculate the permeability, these values of K may provide incorrect indoor radon gas entry rates. Further testing is recommended to determine the dependence of K on the applied Δp, the water-to-cement ratio, the concrete composition, the relative humidity, age and the porosity.

ACKNOWLEDGMENTS

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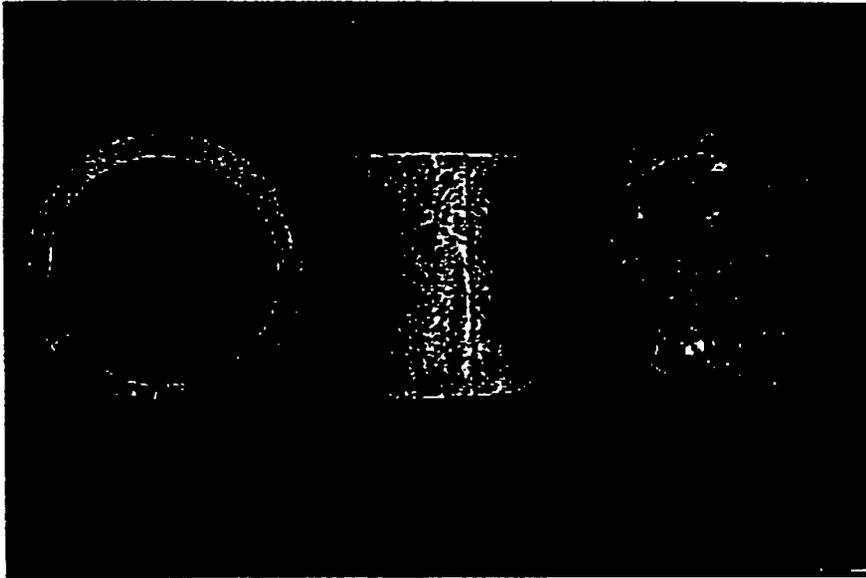
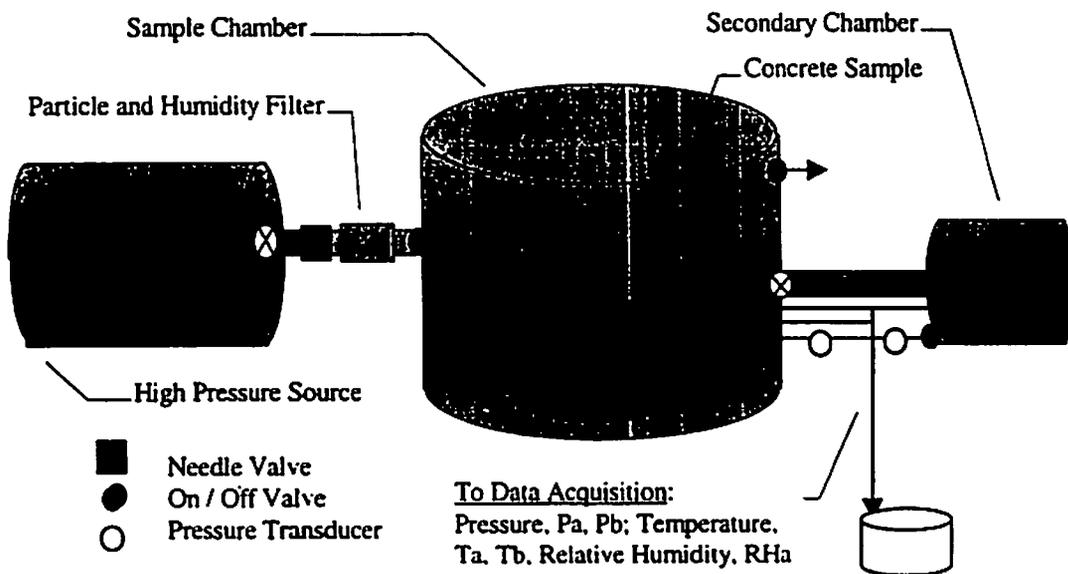**Fig. 1.** Photo of concrete sample in aluminum holder.

Sample Chamber

Secondary Chamber

Concrete Sample

Particle and Humidity Filter

High Pressure Source

■ Needle Valve
● On / Off Valve
○ Pressure Transducer

To Data Acquisition:
Pressure, Pa, Pb; Temperature,
Ta, Tb, Relative Humidity, RHa

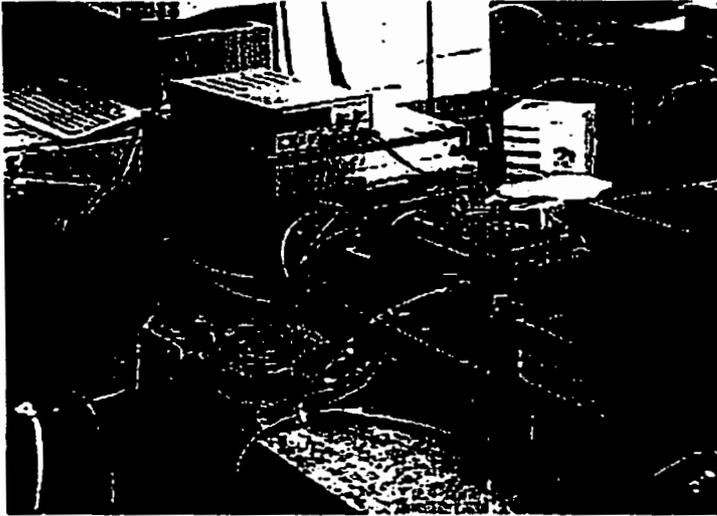**Fig. 2.** Schematic diagram of porosity apparatus.

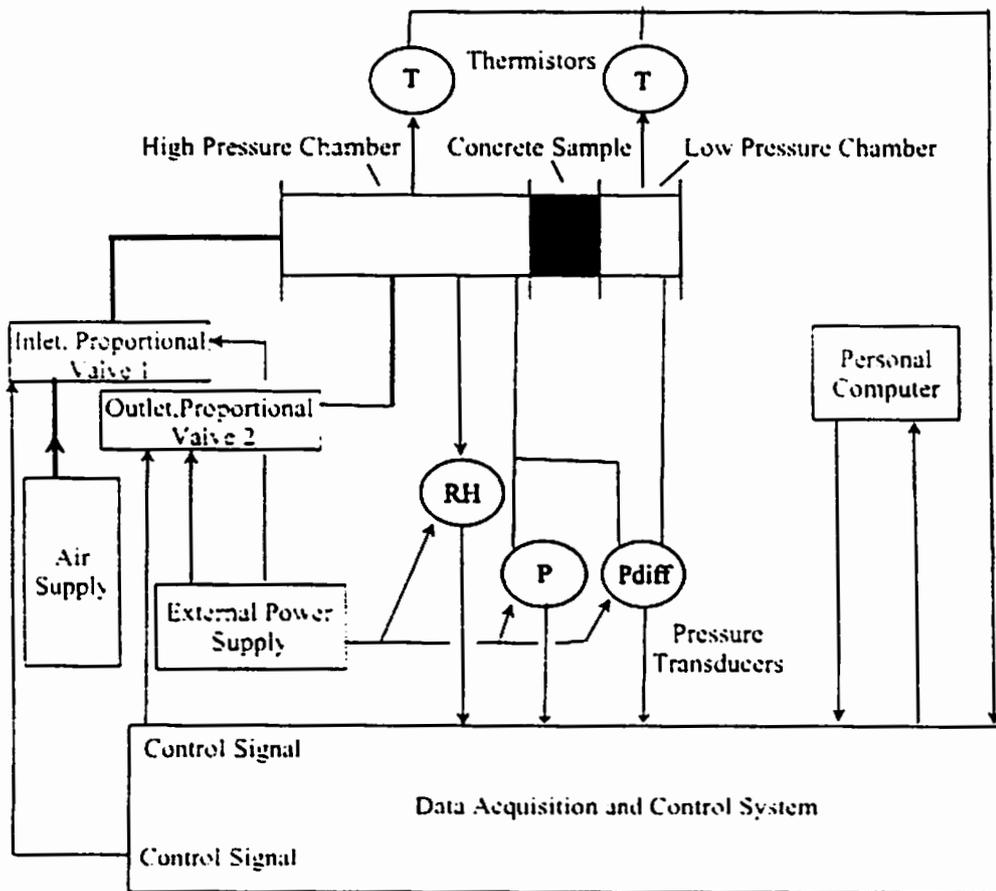**Fig. 3.** Photo of experimental apparatus to measure the air permeability in concrete.

Fig. 4. Schematic diagram of system to measure the concrete air permeability coefficient.
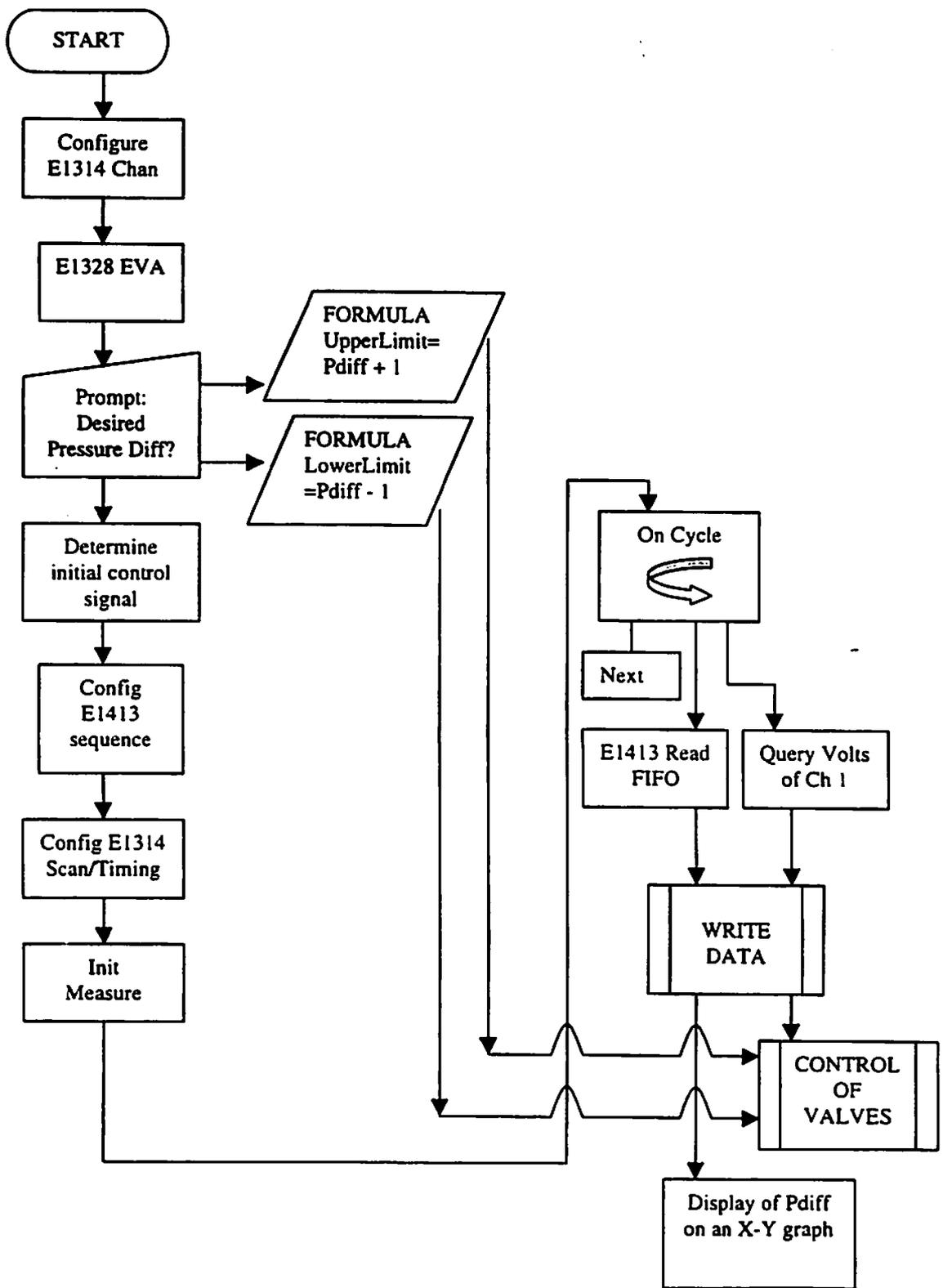
START

Configure
E1314 Chan

E1328 EVA

Prompt:
Desired
Pressure Diff?

FORMULA
UpperLimit=
Pdiff + 1

FORMULA
LowerLimit
=Pdiff - 1

Determine
initial control
signal

Config
E1413
sequence

Config E1314
Scan/Timing

Init
Measure

On Cycle

Next

E1413 Read
FIFO

Query Volts
of Ch 1

WRITE
DATA

CONTROL
OF
VALVES

Display of Pdiff
on an X-Y graph

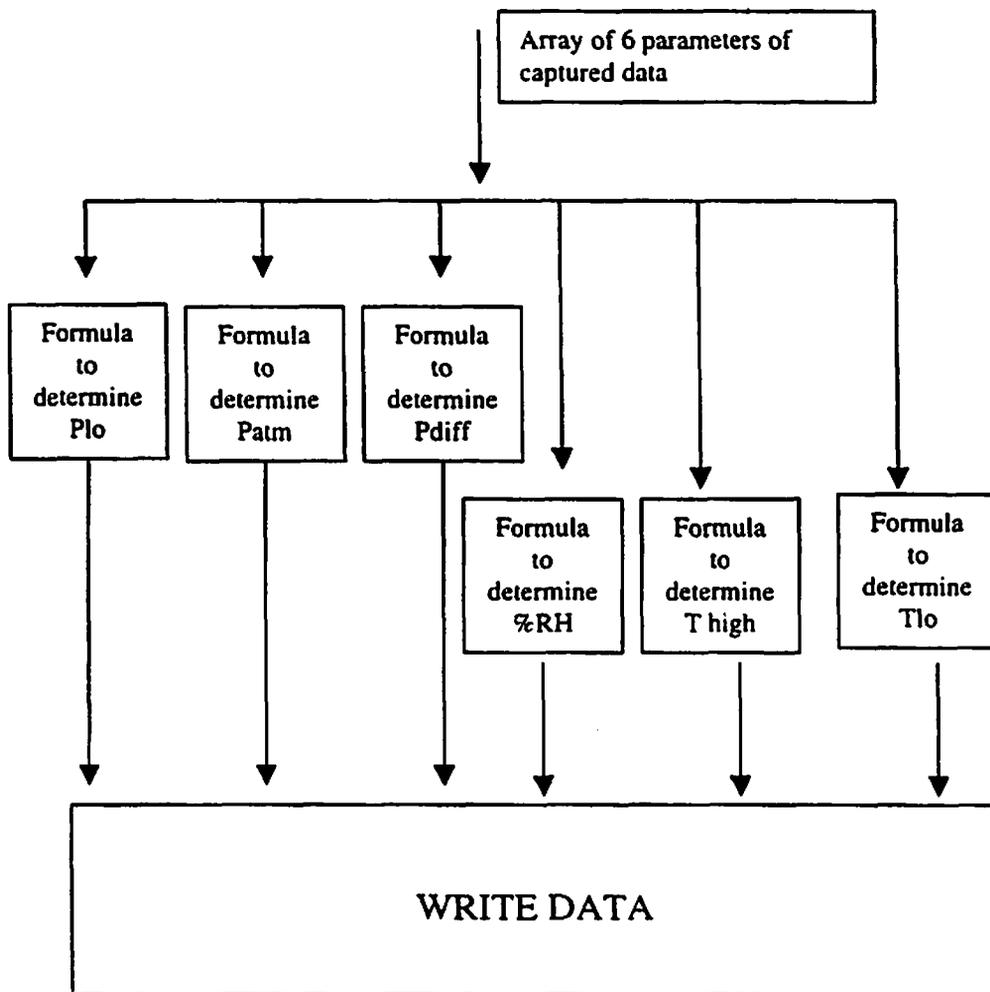**Fig. 5.** Flow chart of HP VEE code used to measure the permeability coefficient.

Fig. 6. Flow chart of the code written in HP VEE for the WRITE DATA user object .
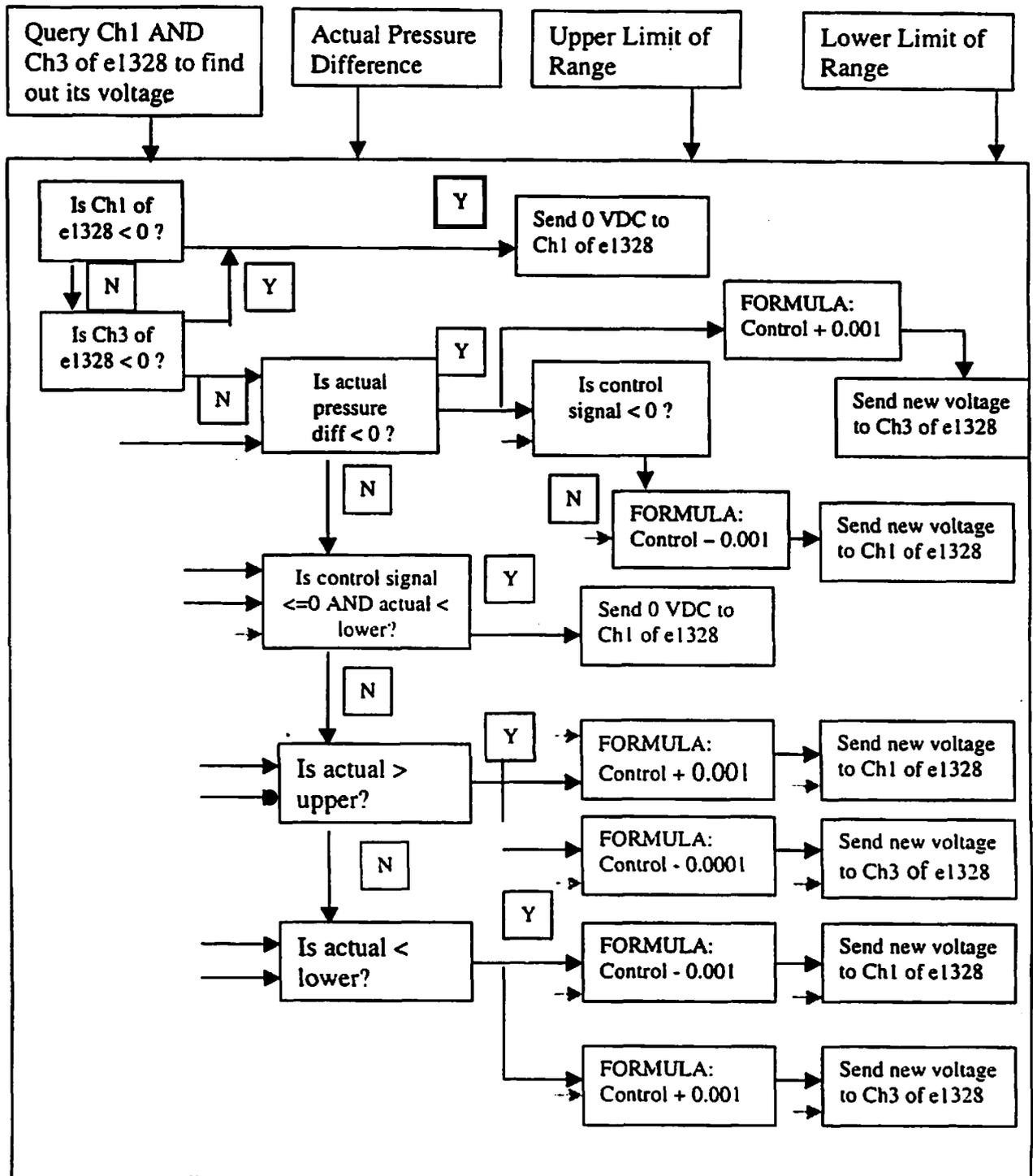
Fig. 7. Flow chart of the code written in HP VEE for the CONTROL OF VALVES user object.

Table 1. Comparison of experimental results.

Porosity, ε (%)	Water/Cement Ratio (w/c)	Δp (Pa)	K (cm^2)	Reference
10.3	0.5	5	5.67×10^{-11}	Present work
		10	6.02×10^{-11}	
11 – 26	0.38 – 0.61	3.6×10^3	$< 1 \times 10^{-11}$	Nielson and Rogers (1991)
26	0.61		4.4×10^{-12}	
17	~ 0.52		6.5×10^{-12}	
18	~ 0.53		8.0×10^{-14}	
17	~ 0.53	3.6×10^3	8.7×10^{-14}	Rogers and Nielson (1992)
22	0.53		3.4×10^{-12}	
26	0.67		3.6×10^{-12}	
23	0.66		4.0×10^{-12}	
24	0.58		4.1×10^{-12}	
11.56	-		2.14×10^{-12}	
19.80	0.61		7.10×10^{-12}	
19.22	0.53		8.77×10^{-10}	
19.74	0.53		4.56×10^{-10}	
15.26	0.67	3.6×10^3	2.04×10^{-12}	Snoddy (1994)
17.08	0.67		1.98×10^{-12}	
14.12	0.66		1.31×10^{-12}	
14.11	0.66		1.11×10^{-12}	
16.67	0.58		2.11×10^{-12}	
14.10	0.58		9.38×10^{-13}	
-	0.37	$0.14 – 0.28 \times 10^6$	$0.4 – 8 \times 10^{-13}$	Sanjuan and Munoz-Martialay (1995)
-	0.37 – 0.52	$0.128 – 0.208 \times 10^6$	$0.6 – 3.5 \times 10^{-11}$	Sanjuan and Munoz-Martialay (1996)
-	0.37	$0.14 – 0.28 \times 10^6$	10^{-12}	Sanjuan and Munoz-Martialay (1997)
12	0.5	10^3	1.35×10^{-12}	Renken and Rosenberg (1995)
21.2	0.5	$1 – 5 \times 10^3$	$0.251 – 5.82 \times 10^{-12}$	Maas and Renken (1997)
7.1 – 13.7	0.5	15 – 100	$6.51 - 15.1 \times 10^{-11}$	Daoud (1998)