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Development of a permeability apparatus for concrete and mortar

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Abstract

A simple and straightforward permeability apparatus for concrete or mortar is described. The necessary equations for the calculation of pressure, dynamic viscosity, flow rate and permeability coefficient are given. Methanol vapor was used as the permeating fluid. The test has been found to be sensitive and repeatable. The proposed cell can be manufactured to fit samples of any dimension. The cell may also be used for any other type of solid porous media. The permeability coefficient of the sample run was found to be greatly affected by w/c and initial moist curing periods. © 2002 Published by Elsevier Science Ltd.

Keywords: Permeability; Concrete; Methanol vapor; Curing; Temperature

1. Introduction and background

Permeability, which can be defined as the ease with by which external elements such as liquids and gases (fluids) penetrate concrete, is considered to be one of the most important properties affecting concrete durability [1–4]. Concrete with higher permeabilities allows faster penetration of gases, liquids and other aggressive materials such as chlorides and sulfates, resulting in rapid corrosion of the reinforcing steel, sulfate attack and other forms of concrete deterioration.

Despite the fact that low permeability is vital for concrete long-term durability, there are no specified values in international standards due to various reasons, which are the following:

1. There is no single approved test that can be used for measuring permeability coefficient of concrete. Numerous tests have been suggested by researchers that can be used to evaluate concrete permeability [5,6]. Permeability is usually expressed in terms of either intrinsic or extrinsic permeability coefficients [7,8]. Examples of these tests are reported by van de Meulen and van Dijk [9], Cabrera and Lynsdale [10] El-Dieb and Hooton [11] and Vuorinen [12] who developed tests that can be used to calculate permeability coefficients of concrete for liquid and gas. Other tests such as ISAT [13], Figg Test [14,15] and Rilem tests [16] give relative results. Although these relative permeability tests are seen to be simple and straightforward, they require great care and consistency in every part of the procedure of the test. The variability of results of some of these tests is high [14]. In addition to this, attempts to correlate these results to permeability coefficients were unsuccessful.

2. The different gas permeability tests are very sensitive to the method of conditioning the samples before the test [5,15]. Moisture content of the concrete samples was reported to affect the results significantly [5,6]. Drying the samples at 105 °C is one procedure that is used to condition the samples before testing especially for gas permeability. No doubt that temperature (105 °C or even less than that) affect the pore structure significantly. Previous works carried out by one of the authors of this current paper [17] confirms this when he investigated the effect of hot climates on pore structure. Earlier finding by Goto and Roy [18] confirmed this finding. However, gas permeability is also greatly influenced by the moisture content of the concrete or mortar samples. If one wants to compare the gas permeability of different samples, moisture content within the pores should be similar. A saturated concrete samples with high w/c ratio would show lower gas permeability results than a dry samples of low w/c ratio due to the presence of more unblocked channels (pores). The authors of this paper will not go into the details of this argument since this paper concentrates mainly on Apparatus Development.

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3. The procedure of testing for permeability coefficients is long [5,10] and prone to human error. Gas or liquid is permeated under pressure from one face and steady-state rate is measured at the other face. Permeability tests require a liquid or gas of known properties and cell that allows no leakage. Flow rate, length of the sample, inlet pressure, outlet pressure, cross-section area and viscosity or density of the fluid are all included in the calculation of permeability coefficient. Because of these variables, the results of the majority of the tests are sensitive to change in test details and limitations of equipment. The tests are therefore seen by many to be long (especially water permeability), relatively complicated and only suitable for research purposes.

In this paper, a simple permeability apparatus is described. The concept of this experimental setup deals with measuring mass loss through concrete specimens sealed over water. Although this concept is not totally new [16,19], the authors have actually derived an equation to calculate permeability coefficient using mass loss results. Details of the apparatus, procedure and samples and derivation of permeability equation are outlined.

2. Testing and apparatus details

2.1. Concept

The concept of this test is based on the fact that at specific temperature and pressure, fluids in a closed container may exist in three phases as solid, liquid and/or vapor. The vapor phase is described by the ideal gas equation as stated below.

$$P = nRT/V \tag{1}$$

where V=the volume of the vapor overlying the liquid, P=the absolute pressure of the vapor, n=the number of molecules or moles, R=the proportional constant known as universal gas constant and T=the absolute temperature of the vapor.

When a fluid is placed in a container that is closed with a solid porous medium such as concrete, pressure will build up to a certain constant value. A pressure difference across the porous medium will exist, causing a flow of the vapor to permeate through the porous medium from the high-pressure face to the low-pressure face according to Darcy's law [20] (see Eq. (2)).

$$\frac{Q}{A} = -\frac{k}{\eta}\frac{\mathrm{d}p}{\mathrm{d}l} \tag{2}$$

where Q=the volume rate of flow (m^3/s), A=the cross-sectional area perpendicular to the flow direction (m^2), k=the intrinsic permeability coefficient (m^2), η=the dynamic viscosity ($\mathrm{N\ s/m}^2$) and $\mathrm{d}p/\mathrm{d}l$=the pressure gradient in the direction of flow ($\mathrm{N/m}^3$).

2.2. The cell

Fig. 1 shows a schematic diagram of the proposed cell. The cell consists mainly of aluminum cup, which is divided into two parts. The top part is greater in diameter than the lower part so that the sample can sit conveniently. The cell may be manufactured to host samples of any dimensions. Although Fig. 1a shows a circular cross-section, a cell of any other cross-section can be manufactured.

2.3. Procedure

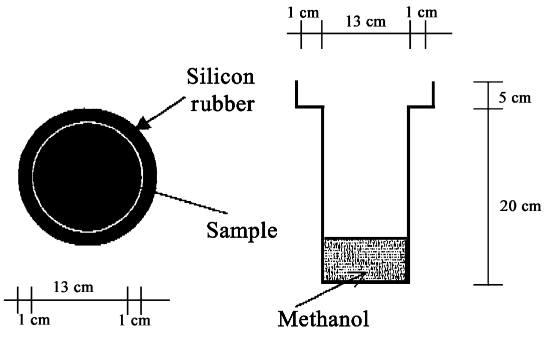
The test procedure can be summarized as follows:

1. The concrete or mortar samples are oven dried at 105 °C to eliminate moisture within the samples. The samples are then placed in a dessicator until the time of testing.

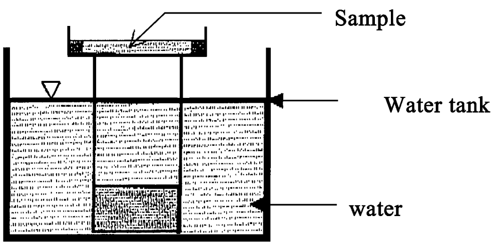
2. A predetermined quantity of methanol is placed in the cell.

3. The samples are placed in the top part of the cell and silicone rubber is poured around it to avoid any leakage. The silicone rubber is allowed to set.

4. When the silicon rubber is set, the testing setup is placed in water of a certain temperature. The lower 2/3 of the cell is submerged, whereas the top face is left exposed to air (Fig. 1b). The rate of mass loss (g/h) is recorded at different time intervals until a steady-state flow result is recorded.



(a): Cell and sample details



(b): Setup details

Fig. 1. Schematic diagram of the UAE permeability cell and the testing setup.

2.4. Permeability calculation

For a noncompressible fluid, Eq. (2) can be integrated [21] to obtain:

$$k = \frac{Q\eta L}{A(P_1 - P_2)} \tag{3}$$

where P_1=the inlet pressure (N/m^2), P_2=the outlet pressure (N/m^2) and L=the length of the sample used in the test (m).

For a compressible fluid or gas, Eq. (3) can be modified using the ideal gas relation (see Eqs. (4) and (5)):

$$PQ = P_n Q_n = \text{Constant} \tag{4}$$

where

$$P_n = \frac{P_1 + P_2}{2} \tag{5}$$

and Q_n is the flow rate at the mean pressure P_n.

By substituting Q=P_nQ_n/P in Eq. (2) and integrating both sides of the equation, the following relation [21] is obtained:

$$k = \frac{2L\eta P_2 Q}{A(P_1^2 - P_2^2)} \tag{6}$$

In Eq. (6), the inlet pressure (P_2), dynamic viscosity (η) and flow rate (Q) can be calculated using the following procedures.

2.4.1. Pressure calculation

The pressure can be calculated using the simple empirical equation known as the Antoine equation [22]:

$$\log_{10}P = A - \frac{B}{T + C} \tag{7}$$

where P=the vapor pressure at given temperature (mm Hg), T=the temperature of the vapor (°C) and A, B and C=constants that depend on the nature of the vapor and the temperature range used in the test.

2.4.2. Dynamic viscosity calculation

The dynamic viscosity [23] can be calculated by the following equation:

$$\eta = [0.807T_r - 0.357\exp(-0.449T_r) + 0.340\exp(-4.058T_r) + 0.018]F_P F_Q/\xi \tag{8}$$

where ξ is defined by Eq. (9):

$$\xi = 0.176\left(\frac{T_c}{M^3 P_c^4}\right)^{1/6} \tag{9}$$

and T_r=the reduced absolute temperature (T_r=T/T_c, where T_c is critical temperature above which the vapor cannot be liquefied no matter how high the pressure), F_p and F_q=correction factors to account for polarity or quantum effects [23], M=the molecular weight of the vapor and P_c=the critical pressure, which is the lowest pressure that will liquefy the gas at its critical temperature.

To obtain the value of these correction factors F_p and F_q, a physical quantity μ_r should be calculated [23], which is defined as follows:

$$\mu_r = 52.46\frac{\mu^2 P_c}{T_c} \tag{10}$$

where μ_r is in debye units, P_c is in bars and T_c is in K and μ is dipole moment, which is given and expressed in debye units[1 deybe being equivalent to 10^{-18} (dyne cm^4)$^{1/2}$= 3.162×10^{-25} (J m^3)$^{1/2}$]. Thus, the physical unit for this property is [(energy)(volume)]$^{1/2}$. Values of F_p values are found for different values of μ_r as follows:

$$\begin{aligned} F_p &= 1 && 0 \le \mu_r < 0.022 \\ F_p &= 1 + 30.55(0.292 - Z_c)^{1.27} && 0.022 \le \mu_r < 0.075 \\ F_p &= 1 + 30.55(0.292 - Z_c)^{1.27} && 0.075 \le \mu_r \\ &\quad \times|0.96 + 0.1(T_r - 0.7)| \end{aligned} \tag{11}$$

Z_c is known as compressibility factor at the critical pressure and temperature. Values of Z_c for different vapors are given in Ref. [23]. The factor F_q, on the other hand, is used only for quantum gases He, H_2 and D_2. For other gases, F_q is taken as unity [23].

2.4.3. Flow rate calculation

The flow rate (Q) for a vapor through the mortar samples is calculated using volume flow rate definition and the ideal gas relation (Eq. (1)):

$$Q = V/t = (m/\rho)/t = m^{\bullet}R_u T/P \tag{12}$$

where V=the volume of vapor (m^3), t=the time duration (h), m=the mass loss (g), $m^{\bullet}$=the rate of mass loss (m/t) (g/h), ρ=the density of vapor (g/m^3), R_u=nR=the gas constant (8.31 J/mol K).

3. Sample runs

3.1. Experimental details

The purpose of this experimental program is to present sample runs demonstrating that the proposed apparatus is

Table 1
Mixture proportions (by mass)

	Mix	NPC	Sand	Microsilica	Slag	Water
Run 1	1	1	3	0	0	0.45
	2	1	3	0	0	0.60
Run 2	3	1	3	0	0	0.6
	4	1	3	0	0	0.5
	5	0.9	3	0.1	0	0.5
	6	0.6	3	0.1	0.3	0.5

Table 2
Methanol properties

Molecular weight (g/mol)	R_u (J/kg K)	T_c (K)	P_c (bar)	μ (debye)	Z_c	A	B	C
32.00	266	512.6	80.90	1.7	0.224	8.0809	1582.2	239.76

The constants A, B and C are obtained from Ref. [24] for the temperature range of 15–84 °C.

sensitive to changes in mix proportions and initial moist curing durations and can be used to evaluate the quality of concrete. Two experimental runs were performed. The first run was aimed at calculating the permeability coefficient for two mixes (different w/c ratios) at four different inlet pressures (i.e., ambient temperature). The goal of the second run was to demonstrate that such apparatus is capable of measuring the differences between the different mix proportions.

3.1.1. Mix proportions

The cementitious material used was plain normal Portland cement (NPC) conforming to British Standard BS12:1991. Sand used was conforming to BS812. In the first run, two mortar mixtures were prepared to investigate the effect of w/c ratio and curing regimes on permeability (see Table 1). The second run was conducted on four mortar mixes of different w/c ratios and cementitious materials, i.e., microsilica and ground granulated blastfurnace slag (ggbs) (see Table 1).

3.1.2. Preparation of samples

The mortar samples were 150 mm in diameter. The length of the samples was kept constant for all samples in each run to eliminate the variation in the results that may be caused by such a variable. The samples were cast, finished, cured and placed at normal laboratory conditions, i.e., 23±2 °C and 70±5% RH. With the exception of those uncured, the

Table 3
Pressure, viscosity, flow rate and intrinsic permeability coefficient calculations

	Curing	Sample	M^*_1 (g/h)	M^*_2 (g/h)	$Q_1\times10^{-10}$ (m^3/s)	$k_1\times10^{-18}$ (m^2)	$Q_2\times10^{-10}$ (m^3/s)	$k_2\times10^{-18}$ (m^2)
20 °C (ΔP = 13,323 N/m^2, η = 0.00118 N s/m^2)	Uncured	Sample 1	0.07	0.11	1.12	13.19	1.80	21.18
		Sample 2	0.07	0.11				
		Average	0.07	0.11				
	3 days	Sample 1	0.03	0.08	5.08	5.99	1.19	13.99
		Sample 2	0.03	0.07				
		Average	0.03	0.07				
	Continuous	Sample 1	0.01	0.05	3.05	3.60	0.81	9.59
		Sample 2	0.03	0.05				
		Average	0.02	0.05				
30 °C (ΔP = 21,424 N/m^2, η = 0.00109 N s/m^2)	Uncured	Sample 1	0.20	0.28	1.98	12.95	2.79	18.22
		Sample 2	0.18	0.26				
		Average	0.19	0.27				
	3 days	Sample 1	0.09	0.20	1.11	7.26	1.94	12.67
		Sample 2	0.12	0.18				
		Average	0.11	0.19				
	Continuous	Sample 1	0.08	0.13	8.06	5.27	1.39	9.11
		Sample 2	0.07	0.13				
		Average	0.08	0.13				
47 °C (ΔP=48,039 N/m^2, η = 0.00096 N s/m^2)	Uncured	Sample 1	0.83	0.89	3.90	8.88	4.25	9.68
		Sample 2	0.75	0.83				
		Average	0.79	0.86				
	3 days	Sample 1	0.40	0.66	1.99	4.53	3.22	7.34
		Sample 2	0.40	0.65				
		Average	0.40	0.65				
	Continuous	Sample 1	0.29	0.50	1.46	3.32	2.40	5.47
		Sample 2	0.30	0.50				
		Average	0.30	0.49				
58 °C (ΔP=81,006 N/m^2, η = 0.00088 N s/m^2)	Uncured	Sample 1	4.22	2.68	1.14	12.53	9.79	10.72
		Sample 2	3.35	3.80				
		Average	3.79	3.24				
	3 days	Sample 1	2.23	2.98	5.69	6.23	8.64	9.47
		Sample 2	1.54	2.74				
		Average	1.88	2.86				
	Continuous	Sample 1	1.01	1.84	3.39	3.71	5.81	6.36
		Sample 2	1.23	2.00				
		Average	1.12	1.92				

$P_1 = 101{,}325+\Delta P$ (N/m^2), $P_2 = 101{,}325$ (N/m^2). M^*_1, Q_1 and k_1 for Mix 1 and M^*_2, Q_2 and k_2 for Mix 2. Sample thickness = 25 mm.

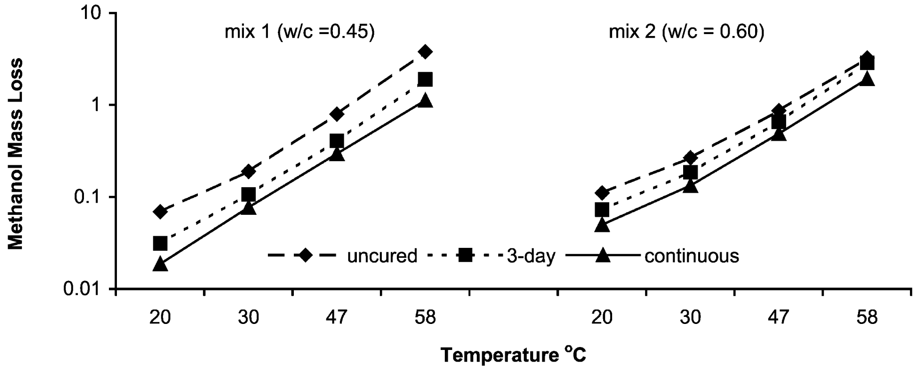


Fig. 2. The influence of temperature on the rate of methanol mass loss (g/h).

samples were covered with polythene sheet to the age of 24 h. They were then demoulded and transferred to a water tank in the same laboratory (20 °C). Three-day cured samples were kept in water for 2 more days, after which they were removed from the water tank and kept uncovered at the normal laboratory conditions to the age of 28 days. Continuously cured samples were kept submerged in water for 28 days. At 28 days of age, the samples of all curing regimes were dried in an oven at 105 °C for 3 days. They were then allowed to cool by placing them in dessicators awaiting testing.

3.1.3. Properties of permeating fluid

In these runs, methanol was chosen to be the permeating fluid mainly because of its low boiling temperature (65 °C). Table 2 shows the properties and constants needed to calculate the pressure, dynamic viscosity and flow rate.

3.1.4. Equations

Rewriting (Eqs. (7), (8) and (12) for methanol in terms of temperature and rate of mass loss (T in K, P in N/m^2, η in N s/m^2 and Q in m^3/s). It should be noted that the value of μ_r is calculated from Eq. (10) (μ_r=4.67$\times$10^{-2}). Then, the value F_p=1.30 was obtained from Eq. (11).

$$P = 10^{\left(8.0809-\frac{1582.2}{512.76+T}\right)} \tag{13}$$

$$\eta = 10^{-7}(4.7169T^{0.618} - 99e^{-8.7593\times10^{-4}T} + 94e^{-7.916\times10^{-3}T} + 5) \tag{14}$$

$$Q = \frac{266\times10^{-3}m^{\bullet}T}{10^{\left(8.0809-\frac{1582.2}{512.76+T}\right)}} \tag{15}$$

where the number 266 is defined in Table 2 as R_u=molecular weight×the universal constant (8.3 J/mol K) [24] (see Eqs. (13)–(15)).

4. Results and discussion

Table 3 presents the steady-state results of methanol mass loss through samples at four different ambient temperatures, namely 20±1, 30±1, 47±2 and 58±2 °C for the first run. Except for those recorded at 58 °C, the variability of the results (compared to the average value) was generally within 5%. At 58 °C, the variability was higher. The reason for such variability is not well understood by the authors. However, 58 °C is considered to be high and very close to the boiling temperature of methanol (65 °C).

Rate of mass loss of methanol increased as temperature increased (see Fig. 2). This is in line with the above argument stating that as temperature increases, pressure also increases, resulting in greater flow rate through samples. Fig. 2 also indicates that higher w/c ratios resulted, as expected, in higher rates of methanol loss at all curing conditions due to the fact that higher water contents results in higher permeable porosity [14]. Uncured samples were most permeable, followed by those cured for 3 days. The 28-day cured samples were found to be least permeable. The apparatus is therefore seen to be suitable and appropriate to differentiate between the different mix proportions (w/c ratios) and curing regimes.

Contrary to what is expected, Table 3 indicates that intrinsic permeability coefficient of any specific sample varies with different temperatures, which are proportional to inlet pressures. Such observations were considered by Dhir et al. [21]. They attributed this to the so-called gas slippage and viscoinertial flow. Apparent intrinsic permeability coefficient (i.e., results calculated according to Darcy's law) had

Table 4
Values of α at different temperatures

Temperature (°C)	α
20	1.355×10^{-16}
30	4.828×10^{-17}
40	1.684×10^{-17}
50	5.713×10^{-18}
60	1.862×10^{-18}
70	7.785×10^{-19}

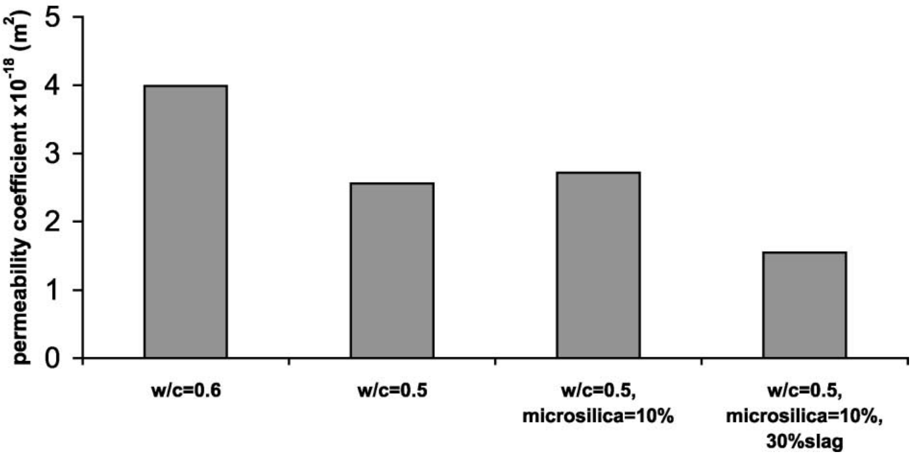


Fig. 3. The influence of curing regime on the rate of methanol mass loss. Sample thickness=25 mm.

to be corrected to obtain proper permeability coefficients. Details of such thing are beyond the objective of this paper. However, the authors are considering further follow-up work to obtain and calculate intrinsic permeability coefficients using the apparatus described in this paper.

For practical purpose, intrinsic permeability coefficient needs to be calculated at one inlet pressure only (i.e., one ambient temperature). For example, at any specific ambient temperature, the intrinsic permeability coefficient (*k*) can be reduced to:

$$k = \alpha \frac{L}{A} m^{\bullet} \tag{16}$$

where

$$\alpha = 2\eta T R_{\mathrm{u}} \frac{P_2}{(P_1^2 - P_2^2)}$$

Example values for α are shown in Table 4.

Taking the above argument into account, the second run was performed at one temperature that corresponds to constant inlet pressure. The ambient temperature was kept at 40 °C corresponding to inlet pressure of (34,450 N/m^2). The results presented in Fig. 3 show that increasing w/c ratio resulted in an increase in permeability. The addition of microsilica to replace part of the cement did not affect the results significantly. Although microsilica is known to reduce permeability when used in slurry form, such effect is expected in the case of adding it in powder form. In addition to this, the combined use of microsilica and ggbs reduced, as expected, the permeability results significantly. A more comprehensive work was carried out by Mills [25]. He measured permeability of different mixes using various tests covering water permeability, water vapor diffusion and gas diffusion. The mix parameters included w/c ratio, fly ash, slag and silica fume. His results indicated that these tests were useful for evaluating concrete mix parameters. Therefore, these tests have the potential for quality assurance. The results of the current work seem to be inline with his outcomes.

5. Conclusions

The proposed apparatus has been demonstrated to be a promising permeability apparatus. It is simple and straightforward. Its dimensions can be modified to fit samples of any dimensions. The test can also be used for concrete, rock or any other solid porous medium. Methanol is a suitable fluid but can be replaced with any other suitable liquid as long as its properties and constants are known. Permeability coefficient can be calculated by means of Eq. (16), which takes into account the rate of mass loss of methanol and dimensions of the sample.

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References

[1] A. Neville, in: V.M. Malhotra (Ed.), Concrete in the Year 2000, 2nd ed., Advances in Concrete Technology, CANMET (Ottawa, Canada) pp. 1–18.

[2] P.K. Mehta, P.J.M. Monteiro, Concrete: Structure, Properties and Materials, 2nd ed., Prentice-Hall, New Jersey, 1993.

[3] Y. Kasai, I. Matsui, Y. Fukushima, H. Kamohara, Air Permeability and Carbonation of Blended Cement Mortars, Proceeding of the 1st International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Minerals By-Products in Concrete, July 1983, ACI SP-79, Montebello, Canada, 1983, pp. 435–451.

[4] M.G. Alexander, B.J. Magee, Durability performance of concrete containing condensed silica fume, Cem. Concr. Res. 29 (1999) 917–922.

[5] R.K. Dhir, P.C. Hewlett, Y.N. Chan, Near surface characteristics of concrete: Intrinsic permeability, Mag. Concr. Res. 39 (141) (1987) 183–195.

[6] P.A. Claisse, H.I. Elsayed, I.G. Shaaban, Test method for measuring fluid transport in cover concrete, ASCE J. Mater. Civ. Eng. 11 (2) (1999) 138–143.

[7] J.G. Cabrera, N. Gowripalan, P. Wainwright, An assessment of concrete curing efficiency using gas permeability, Mag. Concr. Res. 41 (149) (1989) 193–198.

[8] Concrete Society Working Party, Permeability Testing of Site concrete—Review of Methods and Experience, Concrete Society, London, 1988.

[9] G.J.R. van der Meulen, J. van Dijk, A permeability-testing apparatus for concrete, Mag. Concr. Res. 21 (67) (1969) 121–123.

[10] J.G. Cabrera, C.J. Lynsdale, A new gas permeameter for measuring the permeability of mortar and concrete, Mag. Concr. Res. 40 (144) (1988) 177–182.

[11] A.S. El-Dieb, R.D.A. Hooton, High pressure triaxial cell with improved measurement sensitivity for saturated water permeability of high performance concrete, Cem. Concr. Res. 24 (5) (1994) 854–862.

[12] J. Vuorinen, Applications of diffusion theory to permeability tests on concrete: Part I. Depth of water penetration into concrete and coefficient of permeability, Mag. Concr. Res. 37 (132) (1985) 145–152.

[13] BS1881: Part 5.

[14] J.W. Figg, Method of measuring the air and water permeability of concrete, Mag. Concr. Res. 25 (85) (1973) 213–219.

[15] R. Cather, W. Figg, A.F. Marsden, T.P. O'Brien, Improvement to the Figg method for determining the air permeability of concrete, Mag. Concr. Res. 36 (129) (1984) 241–245.

[16] Rilem Recommendation, Water Vapour Permeability of Autoclaved Aerated Concrete, (Rilem/LC7-1978 (E)).

[17] A.M. Alamri, Influence of curing on properties of concrete and mortar in hot climates, PhD Dissertation, Leeds University, UK, 1988.

[18] S. Goto, D.M. Roy, The effect of w/c ratio and curing temperature on the permeability of hardened cement paste, Cem. Concr. Res. 11 (4) (1981) 575–579.

[19] N. Hearn, R.H. Mills, A simple permeameter for water or gas flow, Cem. Concr. Res. 21 (2/3) (1991) 257–261.

[20] R.A. Greenkorn, Flow Phenomena in Porous Media, Marcel Dekker, New York, 1970.

[21] R.K. Dhir, P.C. Hewlett, Y.N. Chan, Near surface characteristics of concrete: Intrinsic permeability, Mag. Concr. Res. 41 (147) (1989) 87–97.

[22] R.M. Fedler, R.W. Rousseau, Elementary Principles of Chemical Processes, 2nd ed., Wiley, New York, 1986.

[23] C.R. Reid, J.M. Prausnitz, B.E. Poling, The Properties of Gases and Liquids, McGraw-Hill, Singapore, 1987.

[24] R.H. Perry, D.W. Green (Eds.), Perry's Chemical Engineer's Handbook, 6th ed., McGraw-Hill, New York, 1984.

[25] R.H. Mills, The permeability of concrete for reactor containment vessels, A report prepared for the Atomic Energy Control Board, Ottawa, Canada, 1983.