

PERFORMANCE CRITERIA FOR STRUCTURAL CONCRETE

Abebe Dinku
 Department of Civil Engineering
 Addis Ababa University

ABSTRACT

In this paper, the durability of concrete in general and the gas permeability of concrete in particular are theoretically explained and some durability test results obtained from laboratory investigation are discussed. A simple and practical gas permeability measurement apparatus, which enables to assess the performance properties of concrete is presented. Test results indicated that curing duration plays a significant role in improving the performance properties of concrete, and it has been shown that compressive strength alone cannot be used to assess the performance properties of concrete accurately.

Keywords: Durability, Permeability, Sorptivity, Concrete, Porosity, Diffusion

INTRODUCTION

Concrete is one of the oldest and most commonly used building materials in the construction industry. Over the centuries, concrete technology has developed from the natural simple use of pozzolanas to the advanced specifications and techniques of today. Its suitability to achieve whatever required shape/sizes in realizing great architectural and engineering designs enables to meet the requirements of construction today and has boundless potential for future development. Concrete being a versatile construction material can be formed in-situ or prefabricated, can be plain, reinforced or prestressed as required.

The quality of concrete is thus a subject of concern both, at the fresh state and hardened state. The requirements in the fresh state are that the mix consistency has to be cohesive in such a way that the concrete can be placed without segregation and does not require excessive compaction effort. In the hardened state, a good concrete should have the desired properties of concrete such as density, porosity, permeability, strength and should provide sufficient resistance against freeze/thaw damage, abrasion and chemical attack. In general terms, for concrete to be classified as good, it has to be durable. It is generally accepted that concrete durability is to a large extent

governed by concrete's resistance to the penetration of aggressive media. Therefore, the assessment of the cover of concrete surfaces is very important in diagnosing concrete structures, due to the fact that they are more responsible to protect the reinforcement from corrosion.

DURABILITY OF CONCRETE

Several arbitrary and conventional definitions are attributed to the term durability. Durability may be defined in a more general way as the ability of a material to remain serviceable for at least the required life time of the structure of which it forms a part [1]. Despite its significant impact, the aspect of concrete durability has not been adequately emphasized in most standard specifications. Concrete mixes are mainly designed to satisfy a certain compressive strength value. However, strength and durability do not necessarily correlate, specially for normal concrete classes.

The ingress of gases, water or ions in aqueous solutions into concrete takes place through pore spaces in the cement paste matrix or micro-cracks. A variety of different physical and/or chemical mechanisms may govern the transport of these media into the concrete, depending mainly on the nature of the pore structure of the concrete, the environmental condition and the degree of saturation of the pore system.

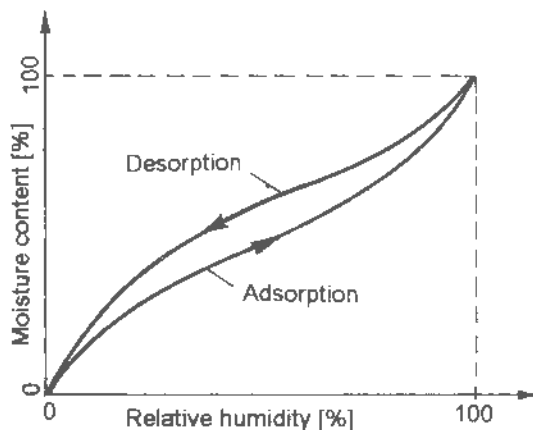
TRANSPORT MECHANISMS IN CONCRETE

It has been generally known, that the properties and performance of concrete are strongly influenced by the moisture content in the concrete. For instance, the rate of cement hydration diminishes markedly with the loss of moisture [2,3], carbonation rates are highest at moisture contents intermediate between dry and saturated [4,5] and the rate of corrosion of reinforcing steel diminishes with a reduction of moisture content [6,7]. Nearly all chemical reactions in the concrete and other physical and mechanical properties are all a function of moisture history in the specimen. Based on these facts, three important transport mechanisms, each of which has an associated flow constant, can be

distinguished in the study of concrete durability: *Absorption and Adsorption, Diffusion and Permeability*.

Absorption and Adsorption

It is generally agreed, that the rate at which unsaturated concrete absorbs water in contact with its surface is largely relevant to various aspects of durability, since it is directly related to the porosity of the specimens. Investigators have tried to study the capillary absorption of a material which is believed to indicate the quality of concrete near an exposed surface. Since the flow of fluids in a porous media are influenced by the moisture content, the ambient relative humidity and temperature, it is of interest to be aware of the state of moisture in a system at a particular condition for accurate investigation. The relation between the moisture content and relative humidity at equilibrium state can be explained using sorption isotherms. Generally S-shaped isotherms are more frequent in cement and concrete specimens. Practically, equilibrium state of a porous media can be reached either during drying, which is known as *desorption* or during wetting, which is known as *adsorption*. Both phenomena are influenced by the temperature of the air, and at the same temperature and relative humidity, more moisture is available during desorption as shown typically in Fig. 1.



Figur 1 Schematic adsorption and desorption isotherms of concrete

Considering a one dimensional case of water absorption into an initially dry porous material, it has been generally shown analytically and experimentally that the volume of water absorbed per unit cross section, I , is proportional to the square root of the time t , and the constant S is known as sorptivity. The

relationship is expressed as:

$$I = S t^{1/2} \quad (1)$$

where, I = volume of water absorbed per unit area (m^3 / m^2)
 S = a material constant called the sorptivity ($\text{m}/\text{s}^{1/2}$)
 t = time (s)

Sorptivity is a property, which is easy to measure accurately and depends on the material property of the test fluid, the initial and final liquid content. Tests for sorptivity can be made in the laboratory using preferably cylindrical specimens with the curved surfaces sealed with a suitable resin-coating and by recording the increase in weight and the depth of penetration at intervals of time.

It is possible to identify the effect of curing and w/c ratio using sorptivity values. For instance, Hall [8] reported a sorptivity value range of 0.70-3.72 mm/\sqrt{h} for various concrete specimens evaluated in the first hour of water exposure, while Torrent *et al.* [9] reported a sorptivity range of 0.402-1.722 mm/\sqrt{h} , where h is time in hour, for various concrete specimens tested after 3 hours of exposure.

The porosity of concrete specimens can be obtained from sorptivity measurements, provided the absorption is allowed to continue until the whole specimen is saturated [10]. It was also possible to establish a relationship between pore radius, r , and water sorptivity, S , as shown in Eq. 2.

$$S = C \sqrt{r} \epsilon \quad (2)$$

where, C = constant describing physical and geometrical properties of the test specimen
 r = concrete pore radius
 ϵ = effective capillary porosity

Diffusion

Diffusion is the process by which a liquid, gas or ion can pass through a porous media due to a concentration gradient. Any transport of gases or water or substances dissolved in water are diffusion processes and are induced by the tendency of equilibrating differences in concentration.

Generally, diffusion of fluids in a porous media can be simply described by the Fick's first law of diffusion, which states that in a steady state condition, diffusivity is constant and the relation is expressed as:

$$J = -D \frac{dC}{dx} \quad (3)$$

where, J = flux [mole per cm²s]
 D = coefficient of diffusion [m²/s]
 dC/dx = potential (concentration) difference along the infinitesimal length dx

Eq. 3 can be re-arranged for homogeneous and isotropic materials at steady state condition as:

$$D = J \frac{x_1 - x_2}{C_1 - C_2} = J \frac{L}{C_1 - C_2} \quad (4)$$

Using the solution of Eq. 4, it is possible, for example, to estimate the time to reach a specific total chloride concentration in concrete. Design nomographs to this effect, which take into account variations in concrete materials, curing, cover, initial chloride content and surface chloride concentration, were proposed in the works of Dhir *et al.* [11].

Permeability

Permeability is a process by which a fluid passes through a porous media due to differences in pressure, and the rate of fluid flow obtained considering differences in pressure is known as permeability coefficient. The permeability study of porous media is applicable in various fields of study, such as in petroleum and chemical engineering, and textile technology. Water and gas permeability measurements of concrete are believed to give sufficient information on the performance properties of concrete by giving qualitative and quantitative description of the relevant parameters, which control the durability of concrete.

Based on D'Arcy equation for flow in a porous media, it was possible to determine the water permeability of concrete using Eq. 5.

$$K = \eta \frac{L}{A t} \frac{V}{\Delta P} \quad (5)$$

For laminar flow of a compressible fluid, the specific permeability coefficient can be simply expressed as shown in Eq. 6.

$$K = \eta \frac{P_0}{\Delta P P_m} \frac{L}{A} \frac{V}{t} \quad (6)$$

Where,

K = specific permeability coefficient [m²]
 ΔP = difference between the inlet (P_1) and outlet pressure (P_2) [bar]
 P_m = mean pressure $(P_1 + P_2)/2$ [bar]
 P_0 = absolute pressure, at which the volume flow rate is determined [bar]
 η = viscosity of the permeating fluid [Ns/m²]
 V = volume of fluid passed through the concrete during the time interval Δt [m³]
 A = cross-sectional area in the flow direction [m²]
 t = time [s]
 L = length of flow [m]

The permeability of concrete is a function of pore size, pore size distribution and connectivity of the pores of the porous media. It has been, therefore, attempted by numerous investigators to relate the permeability of concrete with the pore structure of concrete. According to Reinhardt *et al.* [12], the water permeability coefficient was related to the porosity and the pore structure of test specimens using Eq. 7.

$$K = \epsilon \frac{r_e^2}{8} \quad (7)$$

where,

ϵ = the porosity of the specimen
 r_e = the equivalent pore radius of the test specimen

Summary on the Transport Mechanisms in Concrete

It has been generally accepted that the durability properties of concrete can be basically studied using *diffusion, sorptivity* and *permeability* tests since it is believed that they depend on the actual pore structure of the porous media, i.e. on the porosity and pore size distribution of the media. Each of the methods has its own advantages and shortcomings with regard to its practical applications and test result interpretations.

Diffusion measurements, though reliable, take longer time, are expensive and can only be performed in the laboratory. They are mostly suitable in the study of the corrosion properties of concrete. On the other hand, sorptivity measurements are simple and practical.

Though sorptivity tests are made mainly in the laboratory, they can also be made on site. Comparing Eq. 2 and Eq. 7, it is observed that a reduction in the size of the capillaries has a stronger effect on the permeability rather than on the sorptivity values. This explains the fact that permeability measurements are more sensitive to changes in the concrete mix proportion than sorptivity measurements.

The water permeability measurement of concrete, if made accurately, provides reliable test results. However, it is unsuitable for field conditions since it requires a very long time for stability and it is therefore expensive. In addition, the results of water permeability tests can be distorted due to *self sealing* phenomena, which occur due to hydration process when water is in contact with the unhydrated materials from the test specimens. This is one of the logical drawbacks of using water permeability tests for the durability assessment of concrete.

In recent years, concrete performance assessment using gas permeability measurement is given more importance due to the fact that it provides reliable test results within a short time, it is not expensive when compared to the other durability tests, such as diffusion or water permeability tests, and can be made either on site or in the laboratory. Therefore, the tendencies of current research works are aimed at relating measured gas permeability coefficients of concrete to performance properties of concrete in order to make a prognosis of durability.

TEST METHOD

It has been generally understood that in the choice of gas permeability measurement apparatus theoretical soundness, simplicity in operation, non-destructive nature and portability are essential, since the apparatus is required also for routine quality assessment in addition to the durability investigation. Numerous gas permeability test methods are in practice all over the world and there is a strong desire to standardize gas permeability test methods which can be used on sites and in the laboratory. Due to the complex nature of gas flow in porous media in one hand and as a result of variations in testing procedures (for instance, test conditions, i.e. at high or low pressure, at dried or wet condition and choice of specimen sizes) on the other hand, most of these methods are mainly used in the laboratory for research purposes and they are difficult to use on site. The variations in the test methods are

mainly on: a) the applied test pressure which varies from vacuum to a very high pressure; b) the test position: on the surface or from holes drilled into the concrete and c) pre-treatment of test specimens: e.g. drying at 65 °C, 100 °C or using a drier for few minutes before testing.

The use of low pressure in the gas permeability determination of undried concrete is criticized due to the fact that the capillary pore pressure in the concrete, created due to the presence of moisture, can counter act or at least hinder the free flow of gases through the concrete. It has been reported in the works of Günter, M. *et al.* [13,14], that the capillary pressure due to moisture in the concrete can reach well over 3 bar depending on the w/c ratio. Hence, test methods, which employ very low pressure, specially in undried concrete, are not necessarily theoretically sound, since the free flow of fluid can be counter balanced by the capillary pressure from the concrete itself. Using the Washburn equation, Eq. 8, it can be deduced that the pores that can be intruded at a very low pressure excludes pores less than about 400 nm in diameter, which are very important for the transport of gases in concrete.

$$r = \frac{- (2 \gamma \cos \theta)}{P} \quad (8)$$

where, r = the radius of the intruded pore [mn]
 γ = surface tension of the gas [N/m]
 P = applied external pressure [bar]
 θ = contact angle between mercury and the pore walls

The use of a very high temperature in an oven to dry test specimens is also reported to cause unwanted micro-cracks, which can influence the gas permeability of concrete. The best alternative is to develop a test method, which takes into account the effect of moisture at the time of testing and facilitates the measurements of gas permeability without pre-conditioning.

In this investigation, the performance properties of concrete specimens were evaluated using over-pressure test method. This method was developed to measure the gas permeability of concrete at the University of Stuttgart, Germany. Detailed description of the test method are given in other publications [15,16], and the over pressure test method is schematically shown in Fig. 2.

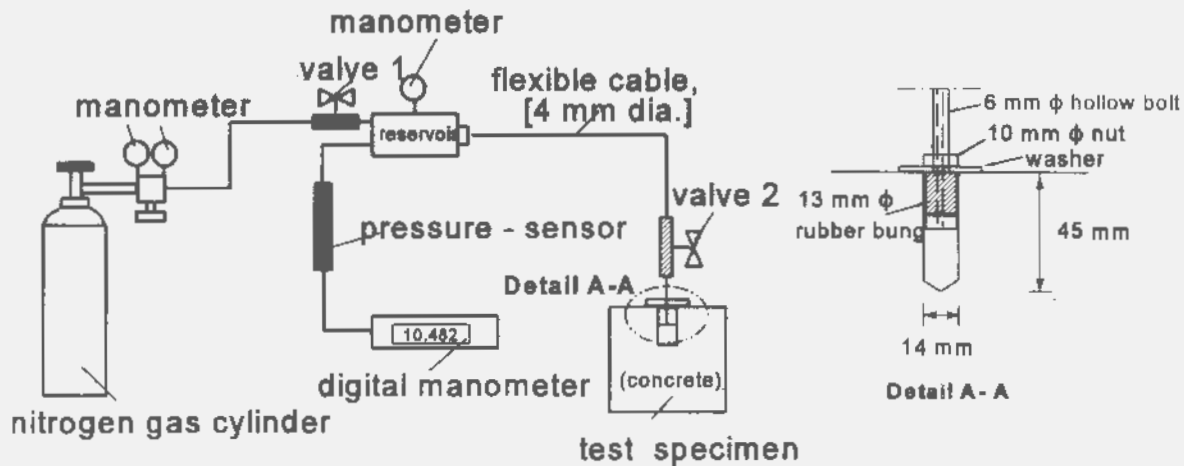


Figure 2 Schematic diagram of the over pressure test method.

The gas permeability measurement apparatus consists of a nitrogen gas supply, an accurate digital display attached to a pressure sensor, a tight gas reservoir, manometers to regulate the flow of gases from the supply, valves to control the flow of gases, hollow flexible connection cable and a hollow steel bolt with expandable dense rubber bung at the end, which is to be fixed into test specimens as shown in Fig. 2 above. By turning the nut, such that the washer lies on the concrete surface, the 13 mm diameter rubber bung is laterally stretched and assures that the top inner surface of the hole is impermeable and thus the flow of gases will only be predominantly through the surrounding concrete cover. It has now been possible to test two or more specimens simultaneously using a single gas reservoir by having a T-connection from the pipe coming from the gas cylinder and connecting to different reservoirs and manometers.

At the day of testing, the test specimens were drilled from the troweled face using a hand drilling machine to the required depth and the remaining dust was sucked out of the hole. Adequate care should be taken not to damage the top surface of the hole during drilling. This problem can be reduced by using a temporary timber cover over the concrete surface and thus avoid direct hammering of the surface using the drilling machine. The depths of the holes and the relative humidity in the test holes were measured before the specimens were fixed into the gas permeability measurement apparatus.

During the test, leaving the two valves open, a nitrogen gas is pumped into the concrete through the drilled hole

at a constant high pressure (~ 10.5 bar) for a few seconds to allow the flow of gas in the concrete to stabilize. Valve 1 was then closed and the rate of pressure drop was recorded, starting when the pressure drop reached 10 bar (i.e. at 10 bar, $t_0 = 0$ sec.) as read from the digital display attached to the reservoir. The pressure drop was further recorded at a pressure interval of 0.5 bar for normal concrete, and at an interval of 0.05 bar for very dense concrete, until it reached around 7.5 and 9.0 bar, respectively. The rate of pressure decay was recorded at least twice for each hole before the specimen is de-mounted from the apparatus and a mean of the results of three different specimens is used to identify the material property, qualitatively or/and quantitatively. It was found that poor quality concrete requires shorter time to reach 7.5 bar than good quality concrete to reach 9.0 bar, which indicates that the time taken for the pressure to drop by a certain amount can be used to compare the permeability property of concrete specimens qualitatively.

The diameter and depth of the holes were chosen to be 14 mm and 45 mm, respectively, due to the following reasons: a) only a very small visual damage on the cover concrete is expected, which can be later restored without difficulty (hence, the method is relatively non-destructive); b) enables visual inspection through the holes; c) 14 mm diameter is a good representative considering maximum aggregate size in concrete and d) the top 45 mm depth was considered to be more susceptible to external effects, such as diffusion and its consequences.

It is an established fact, that the presence of moisture affects the gas permeability measurement and there are disadvantages in pre-conditioning test specimens before testing in order to standardize the moisture content at the time of testing. In this investigation, however, the relative humidity and temperature in the test holes were measured right after the holes were drilled and just before permeability testing, and the values were later used to relate with the moisture content in the concrete. The relative humidity and temperature were measured using commercially available digital thermo-hygrometer, and were displayed on the liquid crystal display (LCD) within few seconds after inserting into the test holes. A total of 15 to 25 minutes were required to drill a hole, measure relative humidity and temperature, and record pressure decay of a single test specimen, depending on the concrete condition at the time of the test.

EXPERIMENTAL INVESTIGATION

Three types of concrete mixes were prepared in the laboratory and adequate number of cubes and cylinders were casted. The test specimens were left one day in the mold, and then cured for 3 or 7 days in a fog room at a temperature of 20°C and 100% relative humidity. The specimens were then stored in a controlled room at a temperature of 20°C and 65% relative humidity until the age of testing. Concrete cubes of 150 mm side were used to determine the compressive strength and specific gas permeability coefficient, while cylindrical specimens having a diameter of 150 mm and a height of 300 mm were used to determine the water absorption coefficient (sorptivity) of test specimens. The mix composition of the three concrete mixes are summarized in Table 1.

TEST RESULTS AND DISCUSSIONS

The 28 days compressive strength, porosity (as determined by the mercury intrusion porosimetry), sorptivity and gas permeability values determined at the age of one year are summarized in Table 2. All values are a mean of three individual test results. The sorptivity values were determined after 24 hours of water exposure. The penetration depths were measured after 72 hours of water exposure and measured by splitting the test specimens longitudinally.

It is an established fact that, compressive strength is a function of w/c ratio and degree of compaction. As observed from Table 2, the test results indicated that compressive strength increases with increase in curing duration and decreases with increasing w/c ratios as expected.

The total porosity values give an indication about the amount of empty pores in test specimens. It has to be noticed that these values indicate all pores, connected and unconnected pores, in the media. Since permeability is a function of connected pores only, it is difficult to establish a relationship between porosity and permeability values. The change in porosity values after three days of curing is less significant. In this respect, it may be practical and reasonable to suggest a minimum of three days of curing to produce less porous concrete.

The results of sorptivity measurements indicated that concrete specimens having higher w/c ratio absorb more quantity of water than those having relatively lesser w/c ratio. A reasonable agreement was reached

Table 1 : Mix composition and fresh concrete property of the mixes

Mix	Cement type	w/c	Cement [kg/m ³]	Aggregate [kg/m ³] ⁽¹⁾		Workability [mm] ⁽²⁾
				fine	Coarse	
A	CEM I 32.5 R	0.46	370	427	1354	360
B	CEM I 32.5 R	0.56	300	458	1374	375
C	CEM I 32.5 R	0.63	270	482	1372	390

⁽¹⁾ a maximum of 16 mm quartzite aggregates were used for all the mixes. Fine aggregate is between 0-2 mm, while coarse aggregate includes all between 2-16 mm diameter.

⁽²⁾ workability was measured using the flow table test.

Table 2 : Summary of Test Results.

Mix	Curing days	Comp. Strength [MPa]	Porosity [%]	Sorptivity [mm/h]	Penetration depth [mm]	Gas permeability coeff. [10^{-17} m^2]
A	1	54.9	13.75	0.98	84	1.040
	3	56.3	12.52	-	-	0.633
	7	60.2	11.87	0.83	73	0.491
B	1	43.3	15.53	1.35	112	2.280
	3	46.0	13.31	-	-	0.682
	7	48.0	11.82	1.07	91	0.613
C	1	36.7	15.47	1.40	113	2.920
	3	38.3	13.79	-	-	1.356
	7	42.8	13.49	1.09	98	0.968

when the sorptivity values were compared with the existing data, despite variations in test specimen sizes, test duration, mix composition and age of testing [8,9]. The measured depths of penetration comply with the results of porosity.

Eq. 6 was modified to accommodate the changes in the new test method (over pressure) and the given values of gas permeability coefficient were determined using Eq. 9.

$$K = 2 \eta \frac{L}{At} \frac{P_s - P_f}{\frac{P_s + P_f^2}{2} - 1} V_{res} \quad (9)$$

where, P_s = absolute starting pressure [bar]
 P_f = absolute finishing pressure [bar]
 V_{res} = the volume of the gas reservoir [m^3] in the testing apparatus.

It has been shown in other investigations that when the flow rates (V/t) were plotted against the squared difference between P_1 and P_2 , where P_1 is the average absolute pressure ($0.5(P_s + P_f)$) and P_2 is atmospheric pressure, straight lines were obtained assuring that the

theory, i.e. D'Arcy's law, and the experimental results are compatible, and the test method provide repetitive and accurate test results.

The gas permeability test results can be used to clearly identify variations in curing duration and w/c ratio. It is even better than compressive strength values in identifying these effects. For instance, the ratio of the highest and the lowest compressive strength values for the investigated concrete specimens were less than 2 ($60.2/36.7 = 1.64$), while a much higher ratio ($2.920/0.491 = 5.95$) were calculated with regard to the gas permeability coefficients (Fig. 3). This indicates that gas permeability values are more sensitive to identify the performance properties of concrete than the traditional compressive strength tests. Similar arguments hold true when the porosity and sorptivity values were compared with the gas permeability coefficients.

It is clearly shown in Fig. 4 that the effect of curing in reducing gas permeability is more significant for concretes having higher w/c ratios than concretes made of low w/c ratios indicating that low quality concretes should be cured for a longer period in order to improve the impermeability property.

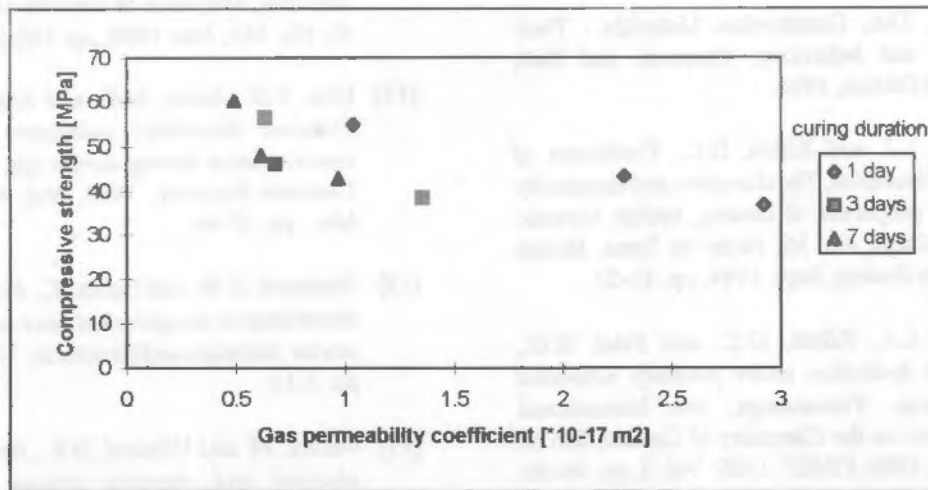


Figure 3 The relation between the 28 day compressive strength and one year gas permeability coefficients

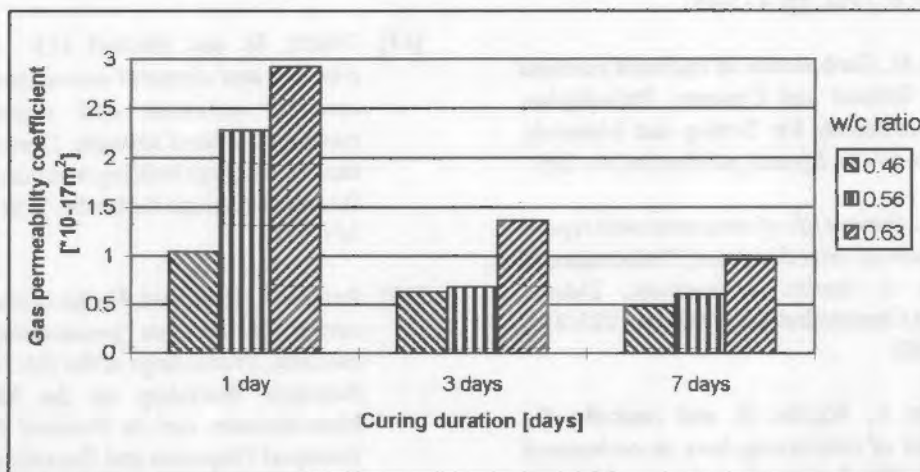


Figure 4 The effect of curing duration on the gas permeability coefficient

CONCLUSIONS AND RECOMMENDATIONS

It has been generally understood that with the increasing importance on producing durable concrete the use of some form of permeability test as a specification compliance would be essential. Based on intensive laboratory investigations, it is possible to formulate gas permeability values as a material property identification, which can be used for the design, construction and inspection of concrete structures. In this respect, the design of the over pressure gas permeability test method is simple, user friendly, relatively non-destructive, gives quick and repetitive test results in the laboratory or/and on sites.

The method is sensitive to changes in curing duration, w/c ratio, cement type and storage conditions and the test results comply with the other durability test results, such as porosity and sorptivity measurement. Although a decrease in gas permeability coefficient were observed with increasing compressive strength, it has been shown that compressive strength alone cannot be a good indicator of concrete performance since, for instance, a dried and surface cracked concrete specimen can have high compressive strength but high gas permeability coefficient as well. A minimum of three days of concrete curing is practical and is recommended to produce concrete with adequate performance properties for general purposes.

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