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Effects of initial curing condition on the fluid transport properties in OPC and fly ash blended cement concrete

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Abstract

This paper presents an experimental study of the influence of two initial curing conditions, wet (fog room) and dry (65% RH and 20 °C), on the transport properties of fluid in normal concrete (100% OPC) and blended cement concrete (OPC/FA). After 28 days initial curing, concrete samples were dried at different relative humidities at 20 °C for about 12 weeks when the equilibrium moisture condition was achieved. Transport properties that include oxygen permeability, water permeability and oxygen diffusion were measured at the equilibrium condition of the samples, and total porosity and degree of saturation were also determined. The initial curing condition has significant effects on the transport properties; in particular the most prominent effects were observed on fly ash blended cement concrete, which performed extremely well when initially cured in wet conditions.

Keywords: Initial curing condition; Permeability; Diffusion; Porosity; Fly ash

1. Introduction

It is generally accepted that concrete durability to a large extent is governed by its resistance against the transport of aggressive elements into its pores. These aggressive elements may be present in either liquid or gaseous form and their transport into concrete takes place via the pore network in the cement paste matrix or via micro-cracks. A variety of factors may govern the transport of these fluids into concrete. Some of the factors are: the substance flowing and its local concentration, the environmental conditions, the pore structure of concrete, the pore radius, the degree of saturation of the pore system and the temperature. Considering the wide range of pore sizes and a varying moisture concentration in the concrete as a function of the climatic exposure conditions, the transport of fluid into concrete is not due to one single mechanism, but several mechanisms may act simultaneously [1].

The pore network of a cement paste matrix provides passage for transport of fluid into concrete and its development depends on a number of factors including the properties and composition of the concrete constituent materials, the initial curing condition and its duration, the age at testing and the climatic exposure during drying and conditioning of the concrete. Parott [2] studied the effect of 1, 3, and 28 days initial moist curing on the permeability of concrete subjected to drying for 6 and 18 months at 60% RH. He found that the permeability of the concrete samples subjected to 3 days curing was about one-sixth of the samples cured for one day only. Similarly, the average permeability of concrete subjected to 28 days initial curing was further reduced to one quarter of the permeability of the samples cured for 3 days. Gowripalan [3] suggested that early age oxygen permeability results could indicate the efficiency of concrete curing. This may be of relevance in that for poorly cured concrete oxygen may have access to the steel reinforcement at a very early age, which might promote early corrosion of the steel reinforcement. The effectiveness of initial curing becomes more important when mineral admixtures like fly ash are used as partial substitution for cement in concrete. Numerous workers including Hassan [4] have reported that fly ash requires a relatively long curing period for its beneficial effect on the performance of concrete to be realised.

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In this investigation three types of concrete mixes based on 100% OPC, 60% OPC & 40% FA, and 50% OPC and 50% FA were used. Concrete samples were initially cured for 28 days under two different conditions; wet cured (in a fog room) and dry cured (at 65% RH and 20 °C). After initial curing, samples were exposed to different climatic conditions (75%, 65%, 40%, and 12% relative humidity at a constant temperature of 20 °C) until the equilibrium moisture condition was achieved. Equilibrated concrete samples were tested in sequence for oxygen diffusion, oxygen permeability, and water permeability. Total porosity and degree of saturation of samples were also determined using vacuum saturation technique [5].

2. Transport properties of fluid in concrete

2.1. Measurements of oxygen permeability

In this investigation, the gas permeameter developed by Cabrera and Lynsdale [6] was used to measure the oxygen permeability of cylindrical concrete samples of 50 mm diameter and 40 mm thick. The coefficient of oxygen permeability was calculated using the modified Darcy's equation (1) as proposed by Grube and Lawrence [7]:

$$K_0 = \frac{2\mu p_{\rm out} QL}{A(p_{\rm in}^2 - p_{\rm out}^2)} \tag{1}$$

where Q is volume flow rate (m^3/s), L is sample thickness (m), $p_{\rm in}$ is pressure at inlet (bar), and A is cross-sectional area of sample (m^2).

The intrinsic permeability of concrete depends on the properties of the flowing fluid, for example the dynamic viscosity. The viscosity of oxygen, μ, at 20 °C is 2.02×10^{-16} N s/m^2, and outlet pressure, $p_{\rm out} = 1$ bar, the coefficient of oxygen permeability.

K_0, is calculated as [6]:

$$K_0({\rm m}^2) = \frac{4.04 \times 10^{-16} QL}{A(p_{\rm in}^2 - 1)} \tag{2}$$

2.2. Measurement of water permeability

Water permeability of concrete was determined by a penetration method. The procedure involved water penetrating the top surface and flowing through the sample under an applied pressure head of 2–4 bars for a time interval as estimated using the values obtained for oxygen permeability and total porosity of the corresponding samples. The intrinsic coefficient of water permeability, $K_{\rm w}$, was calculated as [8]:

$$K_{\rm w} = \frac{d^2 v}{2Th}\left(\frac{\mu}{\rho g}\right) \tag{3}$$

where d is the depth of water penetration (m), T is the time of penetration (s), h is the applied pressure (m), v is the total porosity (fraction), ρ is the density of water (kg/m^3), μ is the viscosity of water (N s/m^2), and g is the acceleration due to gravity (m/s^2).

2.3. Measurements of oxygen diffusion

The diffusion of gases is stimulated by a difference in concentration. In other words, the difference in partial pressure of gases rather than the absolute pressure, controls the diffusion process. The diffusion coefficient not only depends on the open porosity of the concrete (note that diffusion of gases is also possible in fully saturated conditions) but also on the type of gas diffusing in the concrete. There are considerable differences between gases that do not react with the concrete like oxygen and nitrogen, and gases that can condense and/or react with the surface of the hardened cement paste.

In this investigation, measurement of oxygen diffusion was done using the Leeds Oxygen Diffusion cell. During testing oxygen and nitrogen streams are swept through nozzles as provided at the top and bottom of the diffusion cell on the opposite faces of the concrete specimen. The amount of oxygen passing through the specimens to the nitrogen stream is measured using an oxygen analyser, which is an electrochemical device. A zirconium oxide tube is held in a heated furnace at 700 °C and the resulting voltage signals generated by the zirconia are decoded and the oxygen concentration is displayed on a high visibility LED display panel. The instrument is capable of reading between 0.5 ppb and 100% and is auto ranging. The diffusion coefficient, D_0 was calculated as [9,10]:

$$D_0 = \frac{QL}{A\,\Delta c} \tag{4}$$

where D_0 is the coefficient of oxygen diffusion (m^2/s), Δc is the oxygen concentration gradient across the specimen (cc/cc), Q is the rate of oxygen diffusion (m^3/s), L is the sample thickness (m), and A is the cross-sectional area of sample in (m^2).

3. Laboratory investigations

3.1. Materials and mix proportions

Three different concrete mixes were prepared using 0%, 40%, and 50% fly ash content as partial substitution for cement. Ordinary Portland cement from Castle Cement Ltd, UK, fine grained fly ash from Drax, UK, natural quartzite sand as fine aggregate and gravel as coarse aggregate with the maximum size of 14 mm from the deposits of North Nottinghamshire were used as concrete constituent materials.

Table 1
Details of concrete mix proportions

Mix type	OPC (kg/m^3)	FA (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Slump (mm)
OPC	325	0	757	1137	178	57
40 FA	195	130	757	1137	160	56
50 FA	162.5	162.5	757	1137	156	53

The Leeds concrete mix design method [11] based on maximum packing of cement and sand particles for achieving minimum porosity was adopted in this study. The ingredients, OPC or OPC and FA, sand, and gravel, were proportioned by weight ratio of 1:2.33:3.5. The three different mixes based on 0%, 40%, and 50% fly ash content were designed to give the same workability, i.e. a slump value equal to 55 ± 5 mm, Table 1 as below shows the details of concrete mix proportions.

3.2. Casting, curing, and drying of specimens

Concrete slabs of dimensions 400 mm long, 250 mm wide, and 40 mm thick, were cast in a wooden mould. After 24 h the moulds were stripped and slabs were cured for 28 days under two different curing conditions, wet cured (in the fog room) and dry cured (at 65% RH at 20 °C). At the end of this initial curing, 50 mm diameter cylindrical discs were cored out from the slabs. All samples were marked (indicating the mix type, curing condition, and number) and weighed in the air. Four samples from each of the concrete mixes were exposed to different climatic conditions, at 75%, 65%, 40%, and 12% RH at a constant temperature of 20 °C until moisture equilibrium conditions were achieved. It took about 12 weeks for samples to achieve constant weight when conditioned at low relative humidity (12%) and 16 weeks for samples conditioned at higher relative humidities.

3.3. Testing of specimens

At the moisture equilibrium condition, two out of four samples were tested for total porosity, *P*, and the degree of saturation, *S*, using a vacuum saturation technique [5], and the other two samples were tested in sequence to determine the coefficients of oxygen diffusion, oxygen permeability, and water permeability in the diffusion and permeability cells respectively. After measuring the oxygen permeability, water was introduced to the same samples lying in the permeability cell through an inlet slot provided at the top of the cell as shown in Fig. 5. An inlet pressure was applied to force the water to penetrate into the sample for an estimated time interval.

4. Results and discussions

4.1. Initial curing conditions and total porosity and degree of saturation

Fig. 1 shows the values of total porosity of different concrete samples as determined using a vacuum saturation method. Table 2 presents the porosity ratio of different concrete samples, which is the ratio of the total porosity of the dry cured samples and the total porosity of the corresponding wet cured samples. As shown in Table 2, the initial curing conditions affect the total porosity to different degrees for different types of concrete. For OPC concrete, total porosity of dry cured samples was determined in the range of 5–10% higher than that of their corresponding wet cured samples. For 40 FA concrete, the total porosity of dry cured samples was increased by 9–20% as compared to that of wet cured samples, where as a significantly higher porosity value of dry cured 50 FA concrete samples was obtained with respect to the corresponding wet cured samples, it ranges from 23% to 40% higher porosity value.

The values of the degree of saturation, *S* of concrete samples, that were equilibrated at 75%, 65%, 40%, and 12% RH are presented in Table 3. Average value of the degree of saturation of wet cured samples equilibrated at 75% RH was obtained as 68%, where as for the corresponding dry cured samples it was determined as 56%. Similarly, an average value of 15% and 13% was

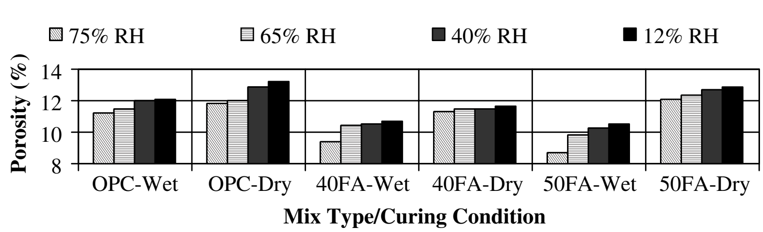

Fig. 1. Total porosity, *P*, of different concrete samples.

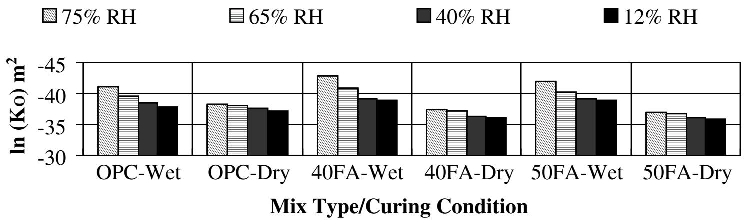

Fig. 2. Oxygen permeability, $\ln(K_{Oxygen})$, of different concrete samples.

Table 2
Total porosity, P and porosity ratio, dry/wet of OPC and FA blended cement concrete cured in wet and dry conditions

RH (%)	Concrete type/curing condition								
	OPC			40 FA			50 FA		
	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet
75	11.23	11.79	1.05	9.42	11.31	1.20	8.72	12.10	1.39
65	11.44	11.97	1.05	10.44	11.44	1.10	9.86	12.34	1.25
40	12.00	12.84	1.07	10.55	11.52	1.09	10.23	12.69	1.24
12	12.05	13.20	1.10	10.69	11.61	1.09	10.52	12.89	1.23

Table 3
Degree of saturation, S of OPC and FA blended cement concrete cured in wet and dry conditions

RH (%)	Measured degree of saturation, S (%)					
	OPC		40 FA		50 FA	
	Wet	Dry	Wet	Dry	Wet	Dry
75	68.87	59.07	70.24	53.23	66.04	51.45
65	59.34	53.01	61.54	49.04	53.03	47.15
40	34.98	29.97	29.59	28.29	27.97	24.54
12	14.71	13.20	11.69	11.61	15.52	12.89

determined respectively for wet cured and dry cured samples, those were equilibrated at 12% RH.

From the above results and discussions, it is concluded that the initial curing condition is one significant factor that controls the porosity and pore network formation of different types of concrete.

4.2. Effects of initial curing condition on fluid transport properties of concrete

Average coefficients of oxygen permeability, water permeability and oxygen diffusion are plotted in Figs. 2–4 respectively. The coefficients of oxygen and water permeability and oxygen diffusions are presented in Tables 4–6; the term used dry/wet is the ratio of the respective coefficients as determined for initially dry cured and wet cured samples. This dry/wet ratio is a useful parameter may be termed as the permeability and/or the diffusion ratio, which is a comparative measure of the effects of the two initial curing conditions on the coefficients of the fluid transport properties in concrete.

As shown in the Tables 4 and 5, the oxygen and water permeability ratios as calculated for OPC and FA blended concrete follow a similar trend but on different scales. For initially dry cured OPC concrete, the coeffi-

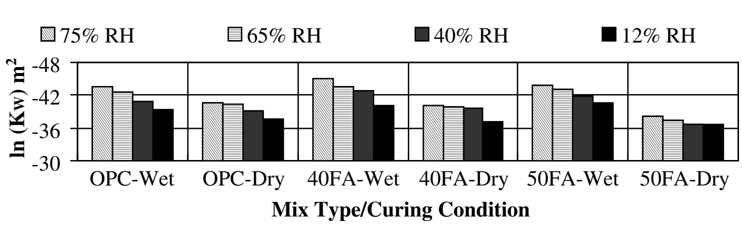

Fig. 3. Water permeability, $\ln(K_{Water})$, of different concrete samples.

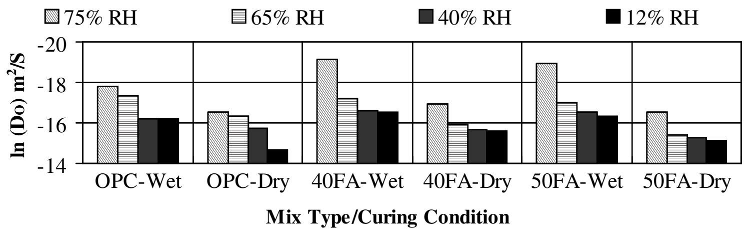

Fig. 4. Oxygen diffusion, $\ln(D_0)$, of different concrete samples.

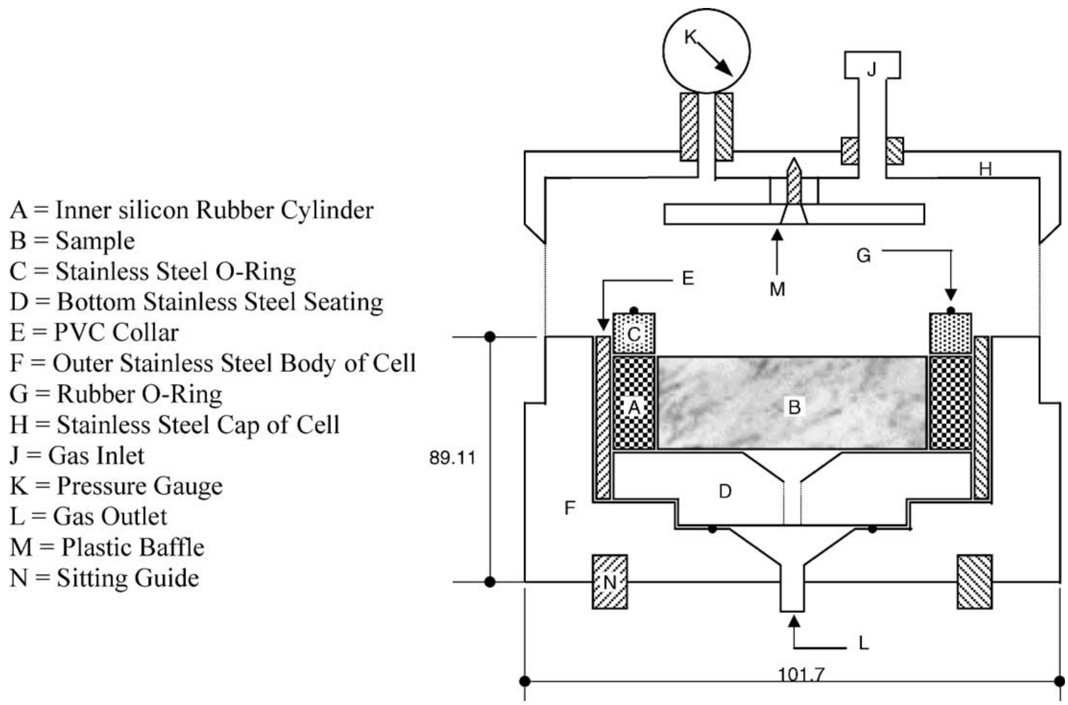

Fig. 5. Schematic diagram of the Leeds cell permeameter.

Table 4
Coefficient of oxygen permeability, K_0 ($\times 10^{-19}$ m^2), and permeability ratio, dry/wet of OPC and blended cement concrete cured in wet and dry conditions

RH (%)	Concrete type/curing condition								
	OPC			40 FA			50 FA		
	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet
75	13.3	230.0	17.3	2.5	518.0	208.9	4.1	906.0	220.4
65	62.1	308.0	5.0	18.2	665.0	36.5	31.8	1070.0	33.6
40	192.0	486.0	2.5	104.0	1720.0	16.5	91.8	2270.0	24.7
12	337.0	772.0	2.3	136.0	2210.0	16.3	117.0	2690.0	23.0

cients of oxygen and water permeability were determined to be of the order of 2–19 times higher than the coefficients obtained for the initially wet cured concrete samples. In contrast, the coefficients of oxygen and water permeability of dry cured FA blended cement concrete were 16–210 times greater than the coefficients of the corresponding wet cured concrete samples. Similarly, Table 6 shows that the coefficient of oxygen diffusion of the dry cured OPC concrete was determined as 1.5–3.7 times higher than the coefficient of diffusion of the wet cured OPC concrete, whereas for FA blended cement concrete, the equivalent increase in the dry/wet ratio ranged from 2.6–11.4 times.

As shown in Tables 4–6, a large difference in the coefficient of fluid permeability and/or diffusion between the dry cured and wet cured concrete was determined

Table 5
Coefficient of water permeability, K_w (×10^{-19} m^2), and permeability ratio, dry/wet of OPC and blended cement concrete cured in wet and dry conditions

RH (%)	Concrete type/curing condition								
	OPC			40 FA			50 FA		
	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet
75	11.0	210.0	19.1	2.8	442.0	157.9	10.0	3080.0	309.5
65	35.0	305.0	8.7	11.4	468.0	41.1	20.9	5140.0	245.9
40	166.0	658.0	3.9	22.8	678.0	29.7	62.0	12300.0	198.4
12	764.0	3870.0	5.1	425.0	6830.0	16.1	231.0	13300.0	57.6

Table 6
Coefficient of oxygen diffusion, D_0 (×10^{-9} m^2s), and diffusion ratio, dry/wet of OPC and blended cement concrete cured in wet and dry conditions

RH (%)	Concrete type								
	OPC			40 FA			50 FA		
	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet	Wet	Dry	Dry/wet
75	18.0	67.0	3.7	4.8	45.1	9.4	5.9	67.6	11.4
65	30.1	80.5	2.7	33.9	120.0	3.5	42.3	205.0	4.8
40	91.6	143.0	1.6	61.7	160.0	2.6	67.8	241.0	3.6
12	133.0	197.0	1.5	64.9	166.0	2.6	79.5	260.0	3.3

when concrete samples were equilibrated at 75% RH. In contrast a small difference between the fluid transport coefficients of dry cured and wet cured concrete samples was observed when they were equilibrated at 40% and 12% RH. As shown in Table 3, an approximately 12% difference was calculated between the average degree of saturation of dry cured concrete samples equilibrated at 75% RH and the average degree of saturation of the corresponding wet cured concrete samples, which resulted in the much higher values of the fluid permeability and diffusion coefficients of dry cured samples relative to wet cured samples. This is probably due to the fact that the wet cured concrete samples when equilibrated at higher RH, have a tight pore network with small pore diameters and exhibit very high degree of saturation.

4.2.1. Effects of initial curing on the performance FA blended cement concrete

From the results as shown in Tables 4–6, it was observed that the fly ash blended cement concrete when initially wet cured performed much better as compared to the wet cured OPC concrete. Average measured values of the coefficient of oxygen and water permeability of wet cured FA blended cement concrete were determined to be one half to one quarter of the measured coefficients of oxygen and water permeability of wet cured OPC concrete. Similarly, the coefficient of oxygen diffusion of FA blended cement concrete was reduced up to one half of the coefficient of oxygen diffusion of OPC concrete. But for dry cured FA blended cement concrete and OPC concrete a completely opposite trend was observed. The coefficient of oxygen and water permeability of dry cured FA blended concrete was about 2 to 4 times greater than the corresponding coefficients of the OPC. The obvious reason for this is that the fly ash blended cement concrete requires prolonged moist curing, in order to take advantage of the beneficial effects of the Pozzolanic activity and pore refinement.

5. Conclusions

Based on the results and the discussion of oxygen permeability, water permeability, and oxygen diffusion of the different concrete, the following conclusions are drawn:

1. Age and exposure conditions for initial curing of concrete are very important particularly for high performance blended concrete.
2. Fly ash blended cement concrete requires prolonged wet curing conditions to produce lower porosity and higher resistance against the transport of aggressive fluid into concrete; prolonged wet curing should therefore achieve higher durability concrete.
3. Drying at different equilibrium moisture conditions plays a significant role in the development of porosity and transport properties of fluid in concrete.
4. This study, based on initial curing and then drying to different equilibrium moisture conditions simulates real life exposure conditions for concrete.

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