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The permeability of fly ash concrete

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Oxygen permeability tests were carried out on plain ordinary Portland cement (OPC) and fly ash concretes at three nominal strength grades. Prior to testing the concretes were subjected to a wide range of curing and exposure conditions. The results emphasize the importance of adequate curing to achieve concrete of low permeability, especially when the ambient relative humidity is low. In addition, the results demonstrate the considerable benefit that can be achieved by the use of fly ash in concrete. Even under conditions of poor curing, fly ash concrete is significantly less permeable than equal-grade OPC concrete, the differences being more marked for higher-grade concretes. Attempts were made to correlate strength parameters with permeability but it is concluded that neither the strength at the end of curing nor the 28-day strength provides a reliable indicator of concrete permeability. A reliable correlation was established between the water to total cementitious material ratio [w/(c + f)] and the permeability of concretes subjected to a given curing and exposure regime.

1. INTRODUCTION

The most prevalent cause of deterioration of reinforced concrete is corrosion of the steel reinforcement. Consequently, the ability of the concrete cover to protect the steel is of paramount importance in determining concrete durability. In order to maintain the steel in a depassivated state the concrete cover must resist the penetration of carbon dioxide and chloride ions to the depth of the steel. Although the chemistry of the concrete may influence the rate of penetration of these agents, physical resistance is provided by the general low permeability of concrete. In addition, if depassivation of the steel occurs, the rate of corrosion will depend on the permeability of the concrete to oxygen and water. The permeability of the concrete cover can therefore be seen as a key factor in determining the overall durability of reinforced concrete.

It has been well established that the partial replacement of ordinary Portland cement (OPC) by fly ash can lead to a significant reduction in permeability of both hardened cement paste [1,2] and concrete [3]. This reduction may be attributed to a combination of the reduction in water content for a given workability and the pore structure refinement due to pozzolanic reaction.

Due to the long-term nature of the pozzolanic reaction, the benefits associated with it are more evident in well-cured concrete, and it has been generally considered that fly ash concrete has a greater susceptibility to poor curing than OPC concrete.

In this study the permeability of fly ash concrete, with a range of fly ash contents, is compared with control OPC concretes of three nominal strength grades. A range of curing and exposure conditions has been used.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

A single source of ordinary Portland cement complying with BS 12 [4] was used throughout this study and its chemical analysis and Bogue compositions are given in Table 1. Three samples of fly ash were used and these were selected to provide ashes with a range of 45 μm sieve retention values. The physical and chemical properties of these ashes are given in Table 1. Thames Valley gravel aggregates were used for all concrete mixes.

2.2 Concrete mixes

Three series of concrete mixes, designated A, G and H, with control mix cement contents of 300, 250 and 350 kg m^{-3}, respectively, and with slumps in the range 30 to 60 mm, were used. Each series comprised six concrete mixes, including the control mix, with a range of fly ash levels and designed to equal 28-day strength (35, 25 and 45 N nominal strengths, respectively). The mix proportions are given in Table 2. Further mix series designated B, C, D, E and F were cast with the same mix proportions as for series A.

2.3 Mixing and casting

Materials were dry-mixed for 1 min prior to the addition of water, after which mixing continued for a further 2 min. Fresh concrete properties were determined 6 min after the addition of water.

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Table 1 Chemical and physical properties of OPC and fly ashes

Elemental oxide	OPC	Fly ash		
		P1	P2	P3
SiO_2	20.55	48.2	48.1	52.4
Al_2O_3	5.07	26.7	24.0	26.0
Fe_2O_3	3.10	11.6	10.6	9.4
CaO	64.51	1.71	6.12	1.69
MgO	1.53	1.62	1.61	1.54
K_2O	0.73	3.18	1.83	2.87
Na_2O	0.15	0.65	0.79	1.32
TiO_2	0.26	0.88	1.00	0.94
P_2O_5	0.19	0.33	0.63	0.21
Mn_2O_3	<0.01	0.02	0.11	0.04
BaO	0.01	0.15	0.14	0.11
SrO	0.18	0.05	0.07	0.03
SO_3	2.53	0.83	0.90	0.85
Cr_2O_3	n.d.	0.03	0.03	0.03
LOI	1.58	4.34	4.49	2.80
Total	100.39	100.41	100.53	100.34
Free lime	0.96			
Total C (included in LOI)	–	3.83	4.10	1.98
45 μm sieve residue	–	11.34	19.45	5.53
Relative density	–	2.46	2.44	2.46
Bogue composition				
C_3S	57			
C_2S	16			
C_3A	8			
C_4AF	9			

Specimens cast from each mix included 100 mm cubes for compressive strength determinations and 150 mm diameter × 300 mm cylinders for oxygen permeability testing.

2.4 Curing and subsequent storage

Following casting, specimens were cured for 24 h in their moulds under damp sacking and polyethylene either in the laboratory at 20°C or in an environmental cabinet at 5°C. After this initial 1-day curing, all specimens were demoulded and subjected to one of the following treatments:

(i) 1 day cure: air-stored immediately after demoulding.
(ii) 3 day cure: moist-cured under damp sacking and polyethylene for further 2 days prior to air-storage.
(iii) 7 day cure: moist-cured under damp sacking and polyethylene for further 6 days prior to air storage.
(iv) Water-cured: immersed in water until test.

The temperature of moist curing and air storage was maintained at either 5 or 20°C. Water-curing was carried out at the same temperature as the moist curing and air storage. The following air-storage conditions were used:

Mix series A, G and H: 20°C and 65% RH.
Mix series B: 20°C and 40% RH.
Mix series C: 20°C and 80% RH.
Mix series D: 20°C and 90% RH.
Mix series E: 5°C and 65% RH.
Mix series F: 5°C and 80% RH.

Table 2 Details of concrete mixes

Mix series	Control mix cement content (kg m^{-3})	Mix No.	Fly ash content	Mix proportions (kg m^{-3})						Estimated 'free' $w/(c+f)$	Workability tests		Wet density (*kg m^{-3}*)	28-day water-cured compressive strength (MN m^{-2})
				OPC	Fly ash	Total water	Thames Valley aggregate				Slump (mm)	CF		
							<5 mm	10–5 mm	20–10 mm					
A to F	300 (35 N)	1	–	300	–	188	655	405	810	0.57	50	0.89	2365	41.5
		2	15% P1	271	48	180	635	411	822	0.51	45	0.89	2370	44.5
		3	30% P1	242	104	173	603	418	835	0.45	40	0.87	2375	45.5
		4	50% P1	196	196	162	577	418	836	0.37	30	0.85	2370	41.5
		5	30% P2	As mix A3							50	0.87	2370	49.5
		6	30% P3	As mix A3							50	0.88	2375	47.0
G	250 (25 N)	1	–	250	–	189	691	402	819	0.68	60	0.91	2335	32.5
		2	15% P1	226	40	181	653	423	845	0.61	55	0.88	2360	33.0
		3	30% P1	202	87	174	633	428	855	0.54	30	0.88	2375	34.5
		4	50% P1	162	162	162	590	438	876	0.44	40	0.87	2370	33.0
		5	30% P2	As mix G3							35	0.89	2360	33.5
		6	30% P3	As mix G3							55	0.88	2370	33.5
H	350 (45 N)	1	–	350	–	188	564	419	837	0.49	40	0.88	2365	50.0
		2	15% P1	314	55	180	564	418	836	0.44	35	0.88	2360	50.0
		3	30% P1	280	120	173	541	420	841	0.39	50	0.88	2375	53.0
		4	50% P1	226	226	162	514	419	838	0.32	30	0.80	2370	48.0
		5	30% P2	As mix H3							35	0.87	2360	50.5
		6	30% P3	As mix H3							35	0.85	2370	50.5

2.5 Testing concrete

Following the various curing periods and air-storage until 28 days the cylinders cast for oxygen permeability tests were sawn to provide three 50 mm thick slices from the top of the specimen. As the permeability of concrete to gases is sensitive to the moisture level within the concrete, the slices were conditioned at 20°C and 65% RH for a further 28 days to ensure that all were tested at a similar moisture condition. The duration and relative humidity of this conditioning period has been found to produce satisfactory data [5]. The specimens that were water-stored for 28 days were also subjected to this conditioning period.

The permeability cell used for the oxygen permeability determinations was developed by Lawrence [5]. It allows a fluid pressure to be applied to one of the flat concrete surfaces while providing a seal to the curved surface. The flow rate from the other flat surface is then measured using a bubble flow meter.

The gas permeability coefficient is determined through a combination of Darcy's law and the Poiseuille equation, the coefficient at a single inlet pressure being given by

$$K_0 = \frac{2QL\eta P_1}{(P_2^2 - P_1^2)A}$$

where K_0 = coefficient of gas permeability (m^2), Q = flow rate (ml s^{-1}), L = specimen thickness (m), η = viscosity of gas (2.02×10^{-4} poise for oxygen), P_1 = outlet pressure (bar), P_2 = inlet pressure (bar) and A = cross-sectional area of specimen (m^2). In this study the flow rate was measured at five absolute inlet pressures of 2, 3, 4, 5 and 6 bar and the parameter $QP_1/(P_2^2 - P_1^2)$ was determined by linear regression.

3. RESULTS

Results of tests on fresh concrete are given in Table 2 together with 28-day water-cured compressive strength data. For the mix series with a control mix cement content of 300 kg m^{-3}, these results are the average results from six mixes (A to F) with the same mix proportions. All concretes had slump values within the target range of 30 to 60 mm although the compacting factors exhibited a fairly wide range. Generally, the average 28-day water-cured strength within a given series is similar for all mixes although concretes with 30% fly ash tend to be of slightly higher strength.

The coefficients of oxygen permeability determined for the top 50 mm slice cut from the concrete cylinders are given in Table 3. These data are presented and discussed in preference to those obtained for the other two slices as it is the properties of the outer layer (cover zone) that will have the greatest influence on durability. The trends shown in the data from the other two discs were similar although generally coefficients were lower and less sensitive to curing effects.

Figure 1 shows the effects of cement content, level of fly ash (P1) replacement and curing temperature on the oxygen permeability of concretes water-cured for 28 days. The results for mixes with a control cement content of 300 kg m^{-3} are the averages from four mix series (A to D) for specimens cured at 20°C and from two mix series (E and F) for specimens cured at 5°C. It is clear from Fig. 1 that the permeability decreases with increases in cement content or the level of fly ash. The permeability of the fly ash concretes with 15, 30 and 50% fly ash were on average reduced by 50, 60 and 86%, respectively, compared with the permeability of the control concrete (no fly ash). This compares with a reduction in permeability of less than 50% when the OPC content of the control mix is increased from 250 (mix G1) to 350 kg m^{-3} (mix H1). This increase in cement content is accompanied by a reduction in the free water/cement ratio from 0.68 to 0.49. Concretes water-cured at 5°C were more permeable compared with those at 20°C, although differences were small for the concretes with zero or 15% fly ash.

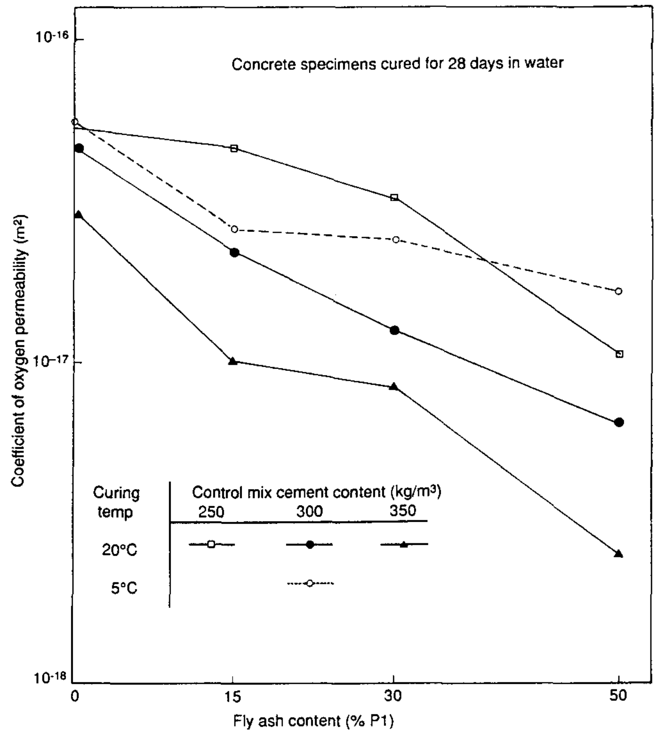

Fig. 1 Permeability of concretes cured in water for 28 days.

The permeability of air-stored concretes was considerably higher (frequently more than one order of magnitude) than water-cured concretes even after 7 days moist curing prior to air-storage. The large differences partially reflect the different curing methods used. Moist curing was carried out by the application of damp sacking and polyethylene to the demoulded specimens. Measurements made by relative humidity meter showed the curing technique to generally provide a relative humidity in excess of 98% but readings below 95% were sometimes recorded (especially after weekends when the sacking was not rewetted). Hence the curing condition would not have been as effective as the saturated condition of

Table 3 Oxygen permeability results for concretes

Mix series	Control cement content (kg m^{-3})	Air-storage conditions		Fly ash content (%)	Oxygen permeability ($\times 10^{-17}$ m^2)			
		Temp. (°C)	RH (%)		Water-cured for 28 days	Air-stored following specified curing period		
						1 day	3 days	7 days
A1	300	20	65	0	4.74	47.5	30.9	24.2
2				15 P1	2.10	34.2	29.0	18.6
3				30 P1	1.10	31.9	17.9	16.5
3				50 P1	0.64	32.2	16.7	8.94
5				30 P2	1.08	26.5	13.6	12.1
6				30 P3	1.98	27.4	17.0	11.8
B1	300	20	40	0	5.11	65.4	32.5	26.2
2				15 P1	2.21	32.3	25.7	16.2
3				30 P1	1.00	36.1	26.9	16.5
4				50 P1	0.91	35.1	11.3	6.02
C1	300	20	80	0	5.68	43.0	29.8	16.9
2				15 P1	2.57	24.3	14.4	13.7
3				30 P1	1.92	22.4	14.3	10.9
4				50 P1	0.80	22.6	6.33	6.49
D1	300	20	90	0	3.52	18.8	14.2	12.1
2				15 P1	1.89	13.6	14.0	9.62
3				30 P1	1.08	12.2	10.9	4.80
4				50 P1	0.25	11.2	7.55	4.60
E1	300	5	65	0	4.85	44.8	25.7	9.14
2				15 P1	2.15	31.2	17.8	5.32
3				30 P1	1.61	43.1	21.9	5.30
4				50 P1	1.73	65.4	28.8	6.53
5				30 P2	2.64	43.9	19.6	10.7
6				30 P3	1.58	31.8	15.4	8.06
F1	300	5	80	0	5.96	42.4	16.0	12.6
2				15 P1	3.04	25.3	6.26	6.60
3				30 P1	3.14	30.3	13.8	3.44
4				50 P1	1.60	21.7	8.12	4.80
G1	250	20	65	0	5.26	65.2	36.2	25.3
2				15 P1	4.60	61.5	32.3	17.3
3				30 P1	3.28	54.1	22.0	16.1
4				50 P1	1.06	40.7	11.4	10.4
5				30 P2	4.97	43.8	22.3	8.06
6				30 P3	2.21	29.1	16.3	21.3
H1	350	20	65	0	2.94	43.7	24.3	19.6
2				15 P1	1.15	24.5	18.4	12.7
3				30 P1	0.84	18.2	9.76	8.59
4				50 P1	0.25	15.8	3.24	3.23
5				30 P2	0.86	14.5	16.3	6.20
6				30 P3	1.05	16.3	12.2	8.60

water-curing, but nevertheless would reflect techniques used on site.

The permeability of air-stored concretes was dependent on the duration and temperature of initial moist curing, the temperature and relative humidity of subsequent air-storage and the level of fly ash replacement. Fig. 2 shows the effect of fly ash content, curing period and temperature on concrete permeability. For specimens cured and air-stored at 20°C the permeability decreases with increases in curing period and fly ash content. Increasing the curing period from 1 day to 3 or 7 days results in an average reduction in the permeability of 37 and 54%, respectively (for concretes stored at 20°C and 65% RH). The reduction in permeability due to the fly ash becomes more marked as the curing period is extended; after 7 days curing, concrete with 50% fly ash

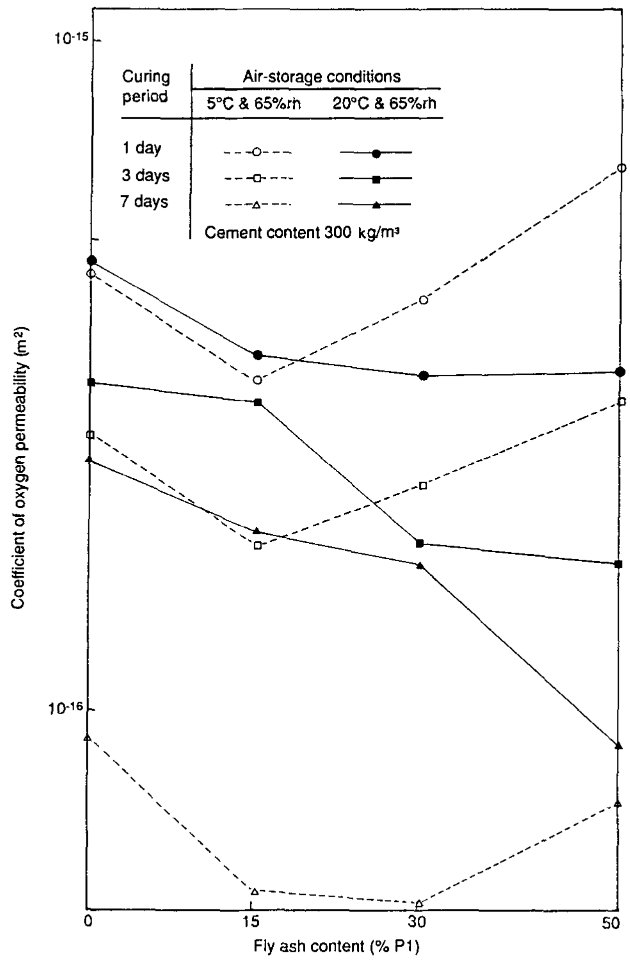

Fig. 2 Effect of fly ash content, curing period and temperature on the permeability of concrete.

was over 60% less permeable than concrete with no fly ash.

The response of the permeability of concrete to storage at 5°C was also dependent on the level of fly ash replacement and the duration of curing. When cured for only 1 day, the permeability of concretes with low levels of fly ash was relatively unaffected by the storage temperature. However, concretes with higher levels of addition showed marked increases in permeability when stored at the lower temperature. As the curing period increases, the concretes stored at 5°C exhibit a proportionately greater reduction in permeability than the concretes stored at 20°C. For concretes cured for 3 days, the permeability of those with higher addition levels of ash also show an increase at 5°C compared with 20°C, although differences were small for concrete with 30% fly ash. For concretes cured for 7 days, all the concretes were less permeable when stored at 5°C compared with 20°C, the differences being quite considerable for concretes with 0 to 30% fly ash.

Fig. 3 shows the effect of cement and fly ash content on the permeability of concretes air-stored at 20°C and 65% RH immediately after demoulding. An increase in the cement content or the proportion of fly ash results in a reduction in the permeability of the concrete. The effects of fly ash on permeability are more marked at the higher cement content (350 kg m^{-3}). For concretes from this mix series (series H) cured for one day, the permeability of the concrete containing 50% fly ash was reduced by 64% compared with the control concrete.

Fig. 4 shows the effect of the relative humidity of storage on the permeability of concretes initially cured for 1 and 7 days. There is little consistent difference between the permeabilities of concretes stored at 40 or 65% RH. However, concretes stored at 80% RH are less permeable than those stored at 65% and, as the relative humidity is increased above 80%, further reductions in permeability are observed.

Comparing the results in Table 3 for concretes with 30% fly ash from the three different sources (designated P1, P2 and P3), it is evident that there is no consistent variation in concrete permeability with the source of fly ash.

Fig. 5 shows the relationship between the compressive strength at 28 days and the permeability for all air-stored concretes (mix series A to H). There is no unique relationship linking these two properties and the regression lines shown in the figure show the influence of fly ash content. For a given air-stored strength, fly ash concrete is significantly less permeable than OPC

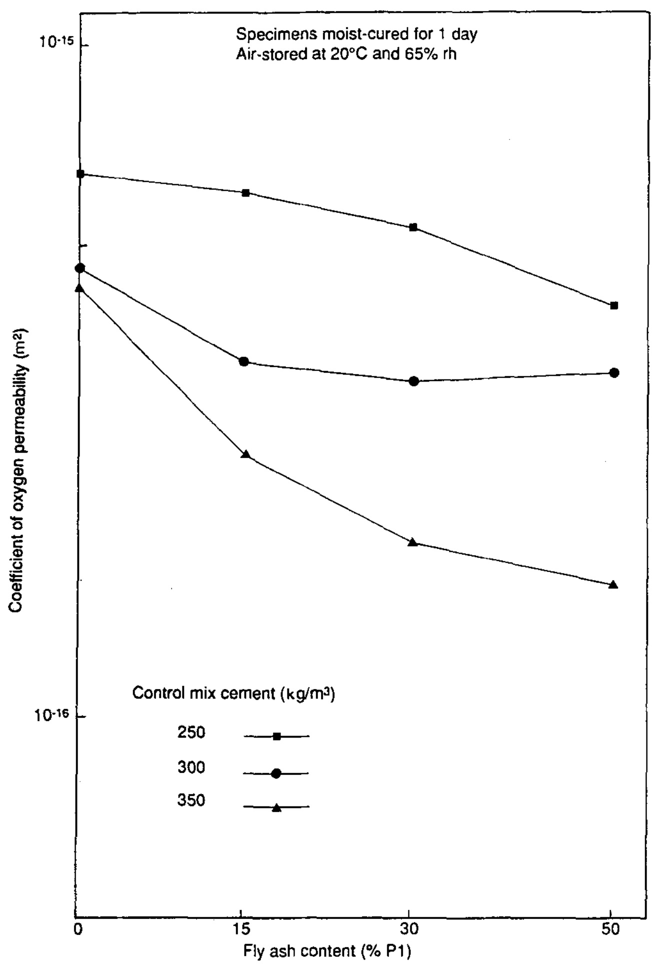

Fig. 3 Effect of cement and fly ash content on the permeability of concrete.

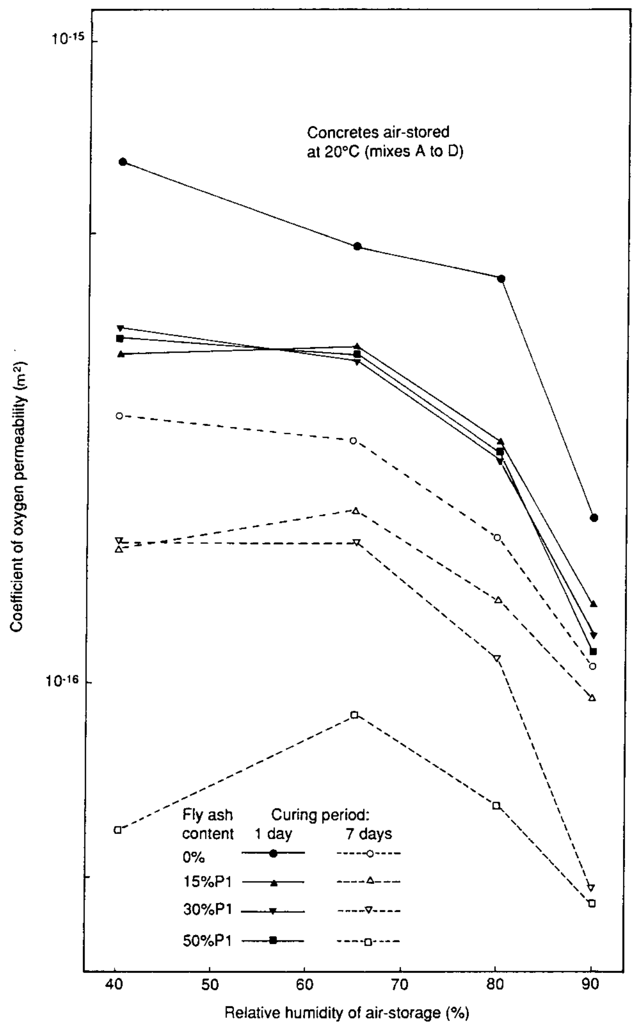

Fig. 4 Effect of ambient relative humidity on the permeability of concrete.

concrete, the difference increasing with fly ash content and strength. In addition, the quality of curing has an effect on the relationship between 28-day strength and permeability. The average 28-day air-stored strength of mixes G1 to G6 (250 kg m^{-3} OPC) after 7 days curing is 34.0 MN m^{-2} compared with 33.8 MN m^{-2} for mixes A1 to A6 (300 kg m^{-3} OPC) cured for 1 day. Despite these almost equal strengths the average permeability of the poorly-cured concretes from mix series A is twice that of the well-cured concretes from mix series G. A further example of the effects of curing on the relationship between strength and permeability can be seen by comparing water-cured and air-stored concretes of similar strength, the water-cured concretes being about one order of magnitude less permeable.

It has been suggested that for OPC and fly ash concretes there is a single relationship between permeability and the compressive strength at the end of the curing period [6]. Fig. 6 shows the relationship between oxygen permeability and strength at the end of curing for OPC and fly ash concretes cured for 1, 3 or 7 days prior to air-storage at 20°C and 65% RH (mix series A, G and H). It can be clearly seen that there is no unique relationship between these properties for OPC and fly ash concrete as the relationship is dependent on the fly ash content. For a given strength at the end of curing, fly ash concrete is considerably less permeable than OPC concrete especially at higher levels of replacement and higher strength.

Fig. 7 shows the relationship between the permeability and the water to total cementitious material ratio [w/(c + f)] for concretes air-stored at 20°C and 65% RH following curing (mix series A, G and H). There appears to be a unique relationship for similarly-cured fly ash and OPC concretes irrespective of the level of replacement. However, the relationship is not independent of

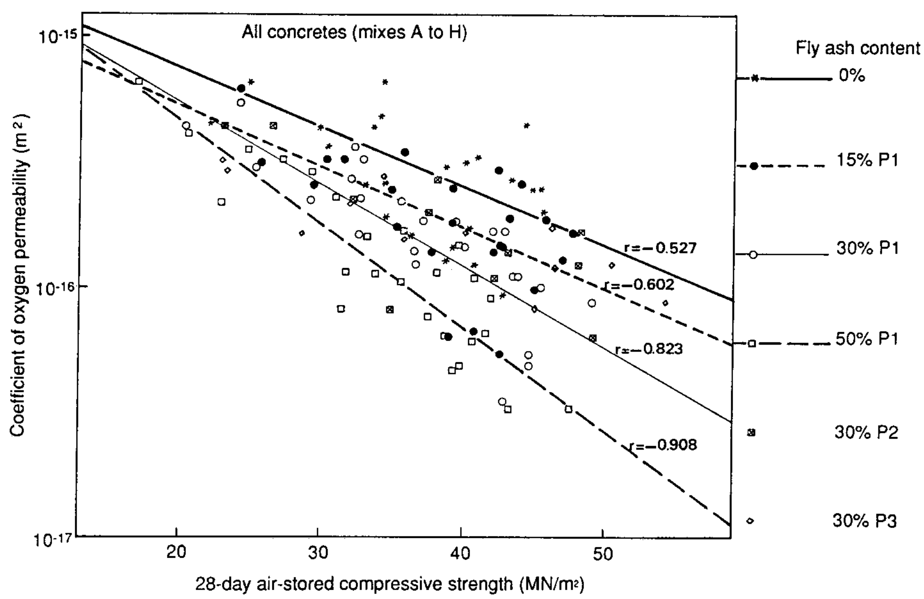

Fig. 5 Relationship between 28-day compressive strength and permeability of concrete.

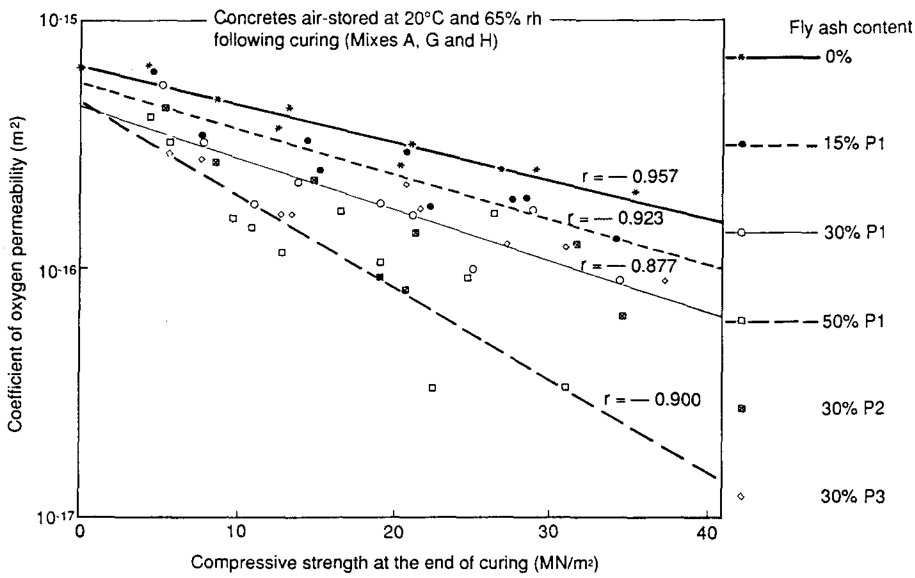

Fig. 6 Relationship between the compressive strength at the end of curing and permeability of concrete.

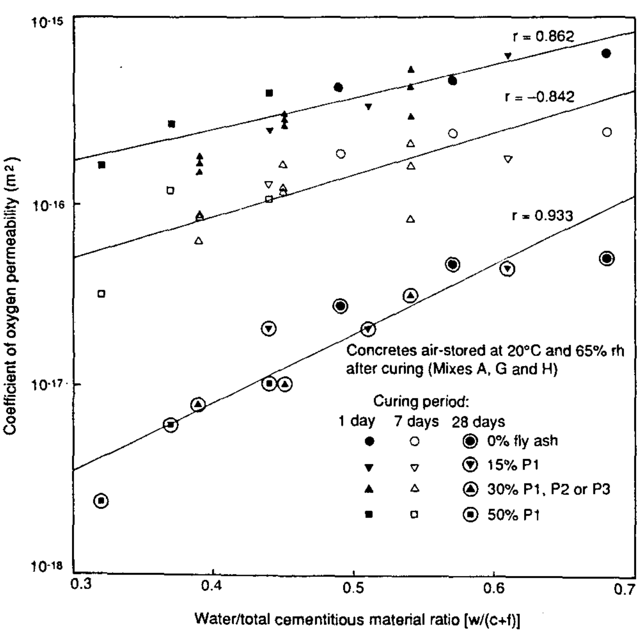

Fig. 7 Relationship between ratio of water to total cementitious material and permeability of concrete.

the extent of curing or the exposure conditions following curing.

4. DISCUSSION

The results clearly indicate the importance of curing to achieve concrete of low permeability and hence good durability, irrespective of whether or not fly ash is present, especially if the ambient relative humidity is low. For concretes stored at 20°C and 65% RH, an increase in curing from 1 to 7 days had the effect of approximately halving the permeability. This concurs with the 'doubling in concrete quality' for the same extension of curing period observed by Ho *et al.* [7] using water sorptivity measurements.

The ambient relative humidity also has a marked effect on the permeability of the concrete. Generally, as the relative humidity increases above about 65% the permeability decreases and more marked reductions are observed at relative humidities above 80%. It has been demonstrated that the hydration of Portland cement ceases below about 80% RH [8] and a similar figure has been suggested for cessation of the pozzolanic reaction [9]. Above 80% RH the rate of both reactions increases dramatically with further increases in relative humidity. The relative humidity at the surface of the concrete also influences the rate of drying of the concrete, the loss of water from concrete during early stages of drying being inversely proportional to the ambient relative humidity [10].

The effect of fly ash on concrete permeability has been clearly demonstrated in this study. For all concretes stored at 20°C, the permeability of fly ash concrete is considerably lower than that of similarly-cured OPC concretes of the same strength grade even when curing is terminated after 24 h. The reduction in permeability of the fly ash concretes is believed to be due to a combination of (i) reduced water content and (ii) refinement of pore structure due to the pozzolanic reaction. The first mechanism will not be affected by curing, and a recent study by one of the authors [9] of OPC and fly ash (30% fly ash) pastes cast at similar free water to total cementitious materials ratios to those used in concrete mixes A1 and A3 (i.e. 0.57 for OPC and 0.45 for fly ash) showed that the fly ash paste had a smaller volume of large pores (>36.8 nm diameter) compared with OPC paste after only 24 h hydration. The pozzolanic reaction is dependent on moisture and is thought to cease at relative humidities below about 80% [9]. However, only the surface layer of a concrete specimen is immediately affected by the ambient relative humidity and, at depths below the surface, sufficient moisture will remain for the pozzolanic reaction (and cement hydration) to occur for some time after the cessation of curing. Consequently, some of the benefits of the pozzolanic reaction will be achieved even in poorly-cured specimens.

Provided adequate curing was given, all the concretes stored at 5°C were actually less permeable than comparable specimens stored at 20°C. Although the hydration of Portland cement is retarded at low temperatures, after sufficient curing periods the quality of concrete is eventually increased due to the improved dispersion of hydration products [10]. This phenomenon reduces the permeability of well-cured concretes at low temperature, especially those with low or zero levels of fly ash.

The pozzolanic reaction is also temperature-dependent, and the results from this study show that the permeability of poorly-cured concretes containing 30 and 50% fly ash is increased by storage at 5°C compared with 20°C, although the concrete containing 30% fly ash consistently remained less permeable than the comparable control concrete. This suggests that at low temperatures slightly longer curing periods may be required for high fly ash contents (50%) if the benefits of the pozzolanic reaction are to be realized.

Attempts were made to establish relationships between compressive strength and permeability but no single relationship exists that is independent of curing history, subsequent exposure condition and fly ash content. The compressive strength at the end of curing is clearly unsuitable as a measure of concrete quality as it assumes that the properties of the concrete are fixed once curing is terminated. The strength at this age takes no account of the ambient conditions following curing and, as was adequately demonstrated in Fig. 4, changes in the relative humidity alone can change the permeability by a factor of three. In addition, when comparing concretes exposed to the same conditions following curing, it is evident that fly ash concretes are considerably less permeable than OPC concretes of the same strength at the end of curing. For example, comparing concretes with a compressive strength of 15 MN m^{-2} after curing (typical of mix series H cured for one day), a concrete with no fly ash might typically be three times more permeable than a concrete with 50% fly ash.

Previous workers [6] have suggested that a single relationship does exist for OPC and fly ash concretes. However, this work was based on low-strength fly ash concretes (18 MN m^{-2} at 28 days) and, as can be seen from Fig. 6 in this study, there is a tendency for the different relationships established for different ash contents to converge at lower strength values.

The 28-day air-stored strength is affected by both the curing and subsequent exposure history of the concrete and is consequently a better estimate of concrete quality than the strength at the end of curing. However, the results in Fig. 5 would suggest that the 28-day air-stored strength is not a reliable indication of concrete permeability (and thus durability). Fly ash concretes are considerably less permeable than equal-strength OPC concretes (by up to five times for concretes with a strength of 50 MN m^{-2} at 28 days). In addition, it was shown that poorly-cured high-grade concretes may be considerably more permeable than well-cured low-grade concretes of the same actual 28-day air-stored strength.

The relationship in Fig. 7 shows that the permeability of concrete for given curing and exposure conditions is closely related to its water to total cementitious material ratio [$w/(c + f)$] irrespective of the level of fly ash replacement. This would suggest that, in terms of permeability, fly ash is as effective as an equal mass of OPC. In practice, the inclusion of fly ash in the mix allows the water content to be reduced, resulting in a lower $w/(c + f)$ ratio and consequently reduced permeability.

Although these results refer to a single source of OPC, it has recently been reported [11] that differences in the composition of Portland cement have a significantly smaller effect on the permeability of concrete than factors such as curing or water/cement ratio.

The results of this study conclusively show that the incorporation of fly ash results in a concrete of reduced permeability and consequently increased durability. Although these improvements are more noticeable in well-cured high-strength concretes, fly ash concrete remains less permeable even when inadequately cured.

These results are consistent with the reported findings [12–14] from an investigation of the properties of OPC and fly ash concretes taken from a range of in-service concrete structures. In each case examined, the cover 50 mm of the fly ash concrete was found to be less permeable than the comparable OPC concrete (comparisons based on equal grade or cementitious content) taken from the same structure.

5. CONCLUSIONS

1. For concretes that were water-cured for 28 days, those containing fly ash were of lower permeability than equal-grade OPC concretes, the differences increasing with fly ash content.

2. The permeability of all the concretes examined was highest at the shortest curing time, especially when the ambient relative humidity was low.

3. As the ambient relative humidity during storage increased, permeability decreased and the effects of the duration of moist curing became less significant.

4. For concretes cured and exposed at 20°C, fly ash concretes were of lower permeability than equal-grade OPC concrete even under the poorest curing and storage conditions (one-day cure, low ambient relative humidity).

5. For concretes cured and exposed at 5°C, concrete with 50% fly ash was more permeable than the equal-grade OPC concrete unless adequate curing was provided. Concretes with 15 or 30% fly ash remained less permeable than the control concrete when cured for only 1 day and exposed to low ambient relative humidity.

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REFERENCES

1. Manmohan, D. and Mehta, P. K., 'Influence of pozzolanic, slag and chemical admixtures on pore size distribution and permeability of hardened cement paste', *Cement Concr. Aggreg.* **3**(1) (1981) 63–67.
2. Marsh, B. K., Day, R. L. and Bonner, D. G., 'Pore structure characteristics affecting the permeability of cement paste containing fly ash'. *Cement Concr. Res.* **15**(6) (1985) 1027–1038.
3. Thomas, M. D. A., Matthews, J. D. and Haynes, C. A., 'The effect of curing on the strength and permeability of PFA concrete', in American Concrete Institute SP-114, edited by V. M. Malhotra (ACI, Detroit, 1989) pp. 191–217.
4. British Standards Institution, 'Specification for Portland Cements', BS 12 (BSI, London, 1989).
5. Lawrence, C. D., 'Measurements of permeability', in Proceedings of 8th International Congress on the Chemistry of Cement', Rio de Janeiro, 1986, Vol. 5, pp. 29–34.
6. Chen Zhang Hong and Parrott, L. J., 'Air permeability of cover concrete and the effect of curing', BCA report C/5 (British Cement Association, Slough, UK, 1989).
7. Ho, D. W. S., Cui, Q. Y. and Ritchie, D. J., 'The influence of humidity and curing time on the quality of concrete', *Cement Concr. Res.* **19**(3) (1989) 457–464.
8. Powers, T. C., 'Structure and physical properties of hardened Portland cement paste', *J. Am. Ceram. Soc.* **41**(1) (1958) 1–6.
9. Thomas, M. D. A., 'The effect of curing on the hydration and pore structure of hardened cement paste containing pulverized fuel ash', *Adv. Cement Res.* **2**(8) (1989) 181–188.
10. Neville, A. M., 'Properties of Concrete' (Pitman, London, 1981).
11. Ben-Bassat, M., Nixon, P. J. and Hardcastle, J., 'The effect of differences in the composition of Portland cement on the properties of hardened concrete', *Mag. Concr. Res.* **42**(151) (1990) 59–66.
12. Thomas, M. D. A., 'An investigation of 10-year old concrete bridges constructed with conventional opc and pulverized fuel ash concretes', *Proc. Inst. Civil Engrs Part 1* **86** (1989) 1111–1128.
13. Thomas, M. D. A., Matthews, J. D., Osborne, G. J. and Cripwell, J. B., 'A comparison of the properties of opc, pfa and ggbs concretes in reinforced concrete walls of slender section', *Mag. Concr. Res.* 42(152) (1990) 127–134.
14. Thomas, M. D. A., 'A comparison of the properties of opc and pfa concrete in 30-year old mass concrete structures', in 'Durability of Building Materials and Components', edited by J. M. Baker, P. J. Nixon, A. J. Majumdar and H. Davies (Spon, London, 1990) pp. 383–394.

RESUME

Perméabilité du béton aux cendres volantes

On a effectué des essais de perméabilité sur des bétons de ciment Portland ordinaire non armé (OPC) et sur des bétons aux cendres volantes de trois classes de résistance nominale. Auparavant, on a soumis les bétons à toute une gamme de conditions de conservation et d'exposition. Les résultats font ressortir l'importance d'une conservation adéquate pour obtenir un béton de faible perméabilité, surtout quand l'humidité relative ambiante est basse, et démontre, de plus, l'avantage considérable que procure l'utilisation de cendres volantes dans le béton.

Même dans des conditions médiocres de conservation, le béton aux cendres volantes est beaucoup moins perméable que le béton OPC de classe équivalente, les différences étant plus marquées pour des bétons de haute classe. On s'est efforcé d'établir une corrélation entre les paramètres de la résistance et la perméabilité, mais on a conclu que ni la résistance en fin de conservation, ni la résistance à 28 jours, ne sont des témoins fiables de la perméabilité du béton. On a établi une corrélation sûre entre le rapport eau/matériau cimenteux total ($w/(c+f)$) et la perméabilité des bétons soumis à une conservation donnée et à un régime d'exposition.