Effect of Curing on Durability of Fly Ash Concrete

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Findings of a 5-year laboratory investigation on the effect of curing on the durability of fly ash concrete are summarized. Three series of concrete mixes were cast such that concretes within a given series were of similar strength grade (nominally 25, 35, or 45 MPa) but varied in fly ash replacement level (0 to 50 percent). Following casting, concrete specimens were subjected to various curing treatments and subsequently were stored at a range of temperatures and relative humidities before testing. To assess the influence of the various curing and storage regimes on concrete performance, concrete specimens were tested for (*a*) compressive strength, (*b*) oxygen permeability, (*c*) carbonation in both internal and external storage, and (*d*) resistance to chloride ingress and steel corrosion. Results indicated that, whereas all concretes required adequate curing to achieve their potential properties, concretes containing fly ash were more sensitive to poor curing. The difference was especially marked at higher levels of replacement (50 percent fly ash), where curtailing the moist-curing period resulted in a large increase in the rate of carbonation and permeability and a marked reduction in compressive strength. Concretes with lower levels of ash (15 to 30 percent) carbonated at slightly higher rates than the control concretes but generally offered lower permeability. Resistance to the penetration of chloride ions increased as fly ash content increased, irrespective of the level of curing applied to the concrete. Poorly cured, low strength grade (C25) concretes with 50 percent fly ash provided greater resistance to chloride than higher grade (C45) concretes without ash. Concretes with moderate levels of fly ash (15 to 30 percent) require no additional curing to provide equal, if not improved, durability compared with opc concrete of the same strength grade. Concretes with higher levels of ash may require extended curing compared with opc concrete, especially if the design of the structure and conditions are conducive to carbonation. Adequately cured, high fly ash content concretes are likely to offer substantially improved durability because of their low permeability and high resistance to chloride ion ingress compared with opc concrete.

It is well established that the use of fly ash in concrete can considerably improve concrete durability. As with all concrete, adequate curing is essential for fly ash concrete if its potential properties are to be realized. However, because long-term benefits associated with a pozzolanic reaction are more evident in well-cured concrete, it generally has been thought that fly ash concrete has a greater susceptibility to poor curing than plain portland cement concrete. Consequently, there is some concern about the durability of fly ash concrete under conditions of curing more closely representative of the range of treatments concrete typically receives on site. Treatment may vary from early stripping of formwork (at low temperatures) with no further curing to keeping concrete covered or spraying with water or curing compounds for longer periods.

This paper reports results from an ongoing laboratory investigation of the effect of curing on the durability of fly ash concrete. Concretes with a range of fly ash levels were subjected to a wide range of curing and subsequent storage conditions before strength and durability testing. Durability testing included (*a*) carbonation, (*b*) permeability, and (*c*) chloride diffusion and corrosion of reinforced concretes in a marine environment (*1*). The results are summarized and demonstrate the effect of curing on the durability of fly ash concrete exposed to different environments.

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EXPERIMENTAL

Three series of concrete mixes were designed using a range of fly ash levels. The mixes' characteristic design strengths were 25 MPa, 35 MPa, and 45 MPa (designated as C25, C35, and C45, respectively) and their slumps ranged from 30 to 60 mm. Mix proportions are presented in Table 1. Cement used for this study was complied with BS 12 for ordinary portland cement (*2*). Three sources of fly ash were selected to provide ashes with a range of 45 microns sieve retention values (5 to 20 percent retained by mass) and otherwise complied with BS 3892: Part 1 (*3*). The chemical compositions of the cement and fly ashes are given in Table 2.

Following casting, specimens were cured for 24 hr in moulds under damp sacking and polyethylene, either in the laboratory at 20°C or in an environmental cabinet at 5°C. After 24 hr, all the specimens were demoulded, kept at the same temperature, and subjected to one of the following curing treatments:

- 1-day cure: air-stored immediately after demoulding,
- 3-day cure: moist-cured under damp sacking and polyethylene for an additional 2 days before air-storage,
- 7-day cure: moist-cured under damp sacking and polyethylene for an additional 6 days before air-storage, and
- water-cured: immersed in water for 28 days.

After curing, specimens were stored in air at various temperatures (5°C or 20°C) and relative humidities (40 to 90 percent relative humidity for 28 days. The following air-storage conditions were used:

Mix Series	*Temperature (°C)*	*Relative Humidity (percent)*
A, G, and H	20	65
B	20	40
C	20	80
D	20	90
E	5	65
F	5	80

At 28 days, the following series of test was carried out:

- Strength: compressive strength testing of 100 mm cubes.
- Carbonation: concrete prisms, 75 × 75 × 200 mm, stored in the laboratory (20°C and 65 percent RH) or outside (sheltered from

TABLE 1 Details of Concrete Mixes

Mix series	Fly ash content	Mix proportions (kg/m^3) OPC	Fly ash	Total water	Thames Valley aggregate < 5 mm	5-10 mm	10-20 mm	Free w/c	Slump (mm)	CF	Density (kg/m^3)	28-day strength (MPa)
A-F	-	300	-	188	655	405	810	0.57	50	0.89	2365	41.5
(C35)	15% P1	271	48	180	635	411	822	0.51	45	0.89	2370	44.5
	30% P1	242	104	173	603	418	835	0.45	40	0.87	2375	45.5
	50% P1	196	196	162	577	418	836	0.37	30	0.85	2370	41.5
	30% P2				As mix A3			0.45	50	0.87	2370	49.5
	30% P3				As mix A3			0.45	50	0.88	2375	47.0
G	-	250	-	189	691	402	819	0.68	60	0.91	2335	32.5
(C25)	15% P1	226	40	181	653	423	845	0.61	55	0.88	2360	33.0
	30% P1	202	87	174	633	428	855	0.54	30	0.88	2375	34.5
	50% P1	162	162	162	590	438	876	0.44	40	0.87	2370	33.0
	30% P2				As mix G3			0.54	35	0.89	2360	33.5
	30% P3				As mix G3			0.54	55	0.88	2370	33.5
H	-	350	-	188	564	419	839	0.49	40	0.88	2365	50.0
(C45)	15% P1	314	55	180	564	418	836	0.44	35	0.88	2360	50.0
	30% P1	280	120	173	541	420	841	0.39	50	0.88	2375	53.0
	50% P1	226	226	162	514	419	838	0.32	30	0.80	2370	48.0
	30% P2				As mix H3			0.39	35	0.87	2360	50.5
	30% P3				As mix H3			0.39	35	0.85	2370	50.5

TABLE 2 Chemical and Physical Properties of OPC and Fly Ashes

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	0.1	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			

direct sunlight and rainfall). Depth of carbonation determined by spraying freshly fractured surfaces with phenolphthalein indicator at 90 days, 1, 2, and 4 years (*4*).

- Permeability: oxygen permeability tests on discs 150 mm in diameter and 50 mm thick cut from 150 × 300 mm cylinders. Specimens conditioned at 20°C and 65 percent RH for 28 days before testing (*5*).
- Corrosion: reinforced concrete prisms, 100 × 100 × 300 mm, placed in tidal zone of marine exposure site (*1*). Composition of seawater: 2.6 g/l SO_4, 18.20 g/l Cl, 0.40 g/l Ca, 1.20 g/l Mg, 9.74 g/l Na, and 0.40 g/l K. Specimens removed at 1, 2, and 4 years. Chloride concentration profile determined by incremental drilling and chemical analysis of collected powder samples. Corrosion of reinforcement determined gravimetrically.

TABLE 3 Summary of Results

Ambient Conditions (to 28 days)		Concrete Grade	Fly ash Content	28 day Strength (% 28 day water-cured strength)			90 day Strength (% 28 day water-cured strength)			Indoor Carbonation depth @ 4 years (mm)			Outdoor Carbonation depth @ 4 years (mm)			Oxygen Pemeability (x $10^{-17}m^2$)			Marine Exposure	
																			D* (x10^{-8} cm^2/s)	C** (wt. % cement)
Temp °C	R.H. (%)			days curing			day curing			days curing			days curing			days curing			days curing	
				1	3	7	1	3	7	1	3	7	1	3	7	1	3	7	1	1
20	40-65	C25	none	89	91	92	91	102	107	25	18	15	13	10	10	65	36	25	15.1	1.7
			15-30	77	93	98	84	102	112	23	17	14	15	12	10	47	23	16	3.2	0.4
			50	70	90	99	73	101	117	>38	22	18	20	15	12	41	11	10	2.5	0.2
		C35	none	82	97	106	84	104	114	16	12	9	10	6	4	56	32	25	9.3	1.7
			15-30	72	91	96	75	96	107	16	13	10	10	7	6	31	22	15	2.5	0.2
			50	61	87	97	63	91	110	23	17	14	13	11	8	31	14	7	2.0	0.2
		C45	none	77	94	102	81	102	105	11	10	9	5	1	1	44	24	20	4.5	0.7
			15-30	73	91	100	77	100	111	12	9	8	6	4	2	18	14	9	1.4	0.1
			50	63	97	109	60	97	112	14	10	8	8	6	2	16	3	3	1.4	0.1
	80	C35	none	82	95	99	92	100	107	12	10	10	7	6	3	43	30	17	N.D	
			15-30	79	97	100	92	107	116	12	11	10	8	6	6	23	14	12		
			50	77	97	103	86	110	131	16	12	11	10	7	5	23	6	6		
	90	C35	none	85	97	101	98	113	119	12	10	8	7	5	4	19	14	12	N.D	
			15-30	86	101	105	104	116	128	11	10	9	7	5	4	13	12	7		
			50	85	96	102	99	114	123	12	11	11	9	9	7	11	8	5		
5	65	C35	none	53	82	102	N.D			16	11	9	9	6	4	45	26	9	N.D	
			15-30	42	83	98				20	13	9	11	7	5	38	19	7		
			50	40	69	96				22	16	12	14	9	7	65	15	7		
	80	C35	none	70	85	91	N.D.			16	14	11	11	8	6	42	16	13	N.D	
			15-30	63	86	95				15	11	8	9	6	5	28	10	10		
			50	56	76	97				17	10	9	10	7	5	22	8	5		

N.D. - not determined
D* - chloride diffusion coefficient calculated from chloride concentration profile after 2 years exposure; C** - chloride content at depth 26-31mm after 2 years exposure.

RESULTS

Results for tests for three types of concrete are summarized in Table 3: (*a*) no fly ash (control mixes), (*b*) normal fly ash replacement levels (average results for concretes with 15 to 30 percent fly ash), and (*c*) high fly ash content (50 percent).

Strength

The strength of all concretes decreased as their curing period was curtailed (Table 3); however, the strength of fly ash concrete was more adversely affected by inadequate curing, especially at higher levels of fly ash (50 percent and for those concretes exposed to low temperatures or low relative humidities after curing. Other researchers have observed similar trends for fly ash concrete and mortars (*6–9*).

Concretes with traditional levels of fly ash (15 to 30 percent) generally exhibit comparable strength loss to opc concretes, provided the concretes are cured for at least 3 days. Fly ash concretes cured for only 1 day before exposure to low relative humidities (or low temperatures) lose more strength than similarly treated opc concretes.

Under favorable exposure conditions (20°C and 80 or 90 percent relative humidity), fly ash concrete requires no additional curing to achieve strength comparable to opc concrete, even at high levels of replacement.

In practice, only the surface of large sections of concrete will lose moisture at rates similar to those of small specimens used in this study. The internal bulk of the concrete will retain its moisture for a much longer period. Consequently, the strength of large sections are less affected by the quality of curing. In addition, the temperature rise caused by the heat of hydration plays an important part in determining the in situ strength of large concrete sections. Except in slender sections, the effect of a temperature rise is likely to overshadow the effect of low ambient temperatures, which retard fly ash concrete strength development more severely than opc concrete. Therefore, additional curing required by fly ash concretes in order to achieve similar strength as opc concretes may be necessary only in slender sections.

Permeability

The permeability of concrete is an important parameter in determining its durability, because it provides a measure of the concrete's physical resistance to the ingress of deleterious agents (carbon dioxide, chlorides, and sulphates) and the movement of oxygen and water, which is required for corrosion. Although there is no single test for assessing the durability of concrete exposed to different conditions, permeability is generally considered the best parameter for characterizing the ability of the concrete to resist deterioration (*10*).

The oxygen permeability results in Table 3 indicate a very marked dependence on the duration of curing. Increasing the period

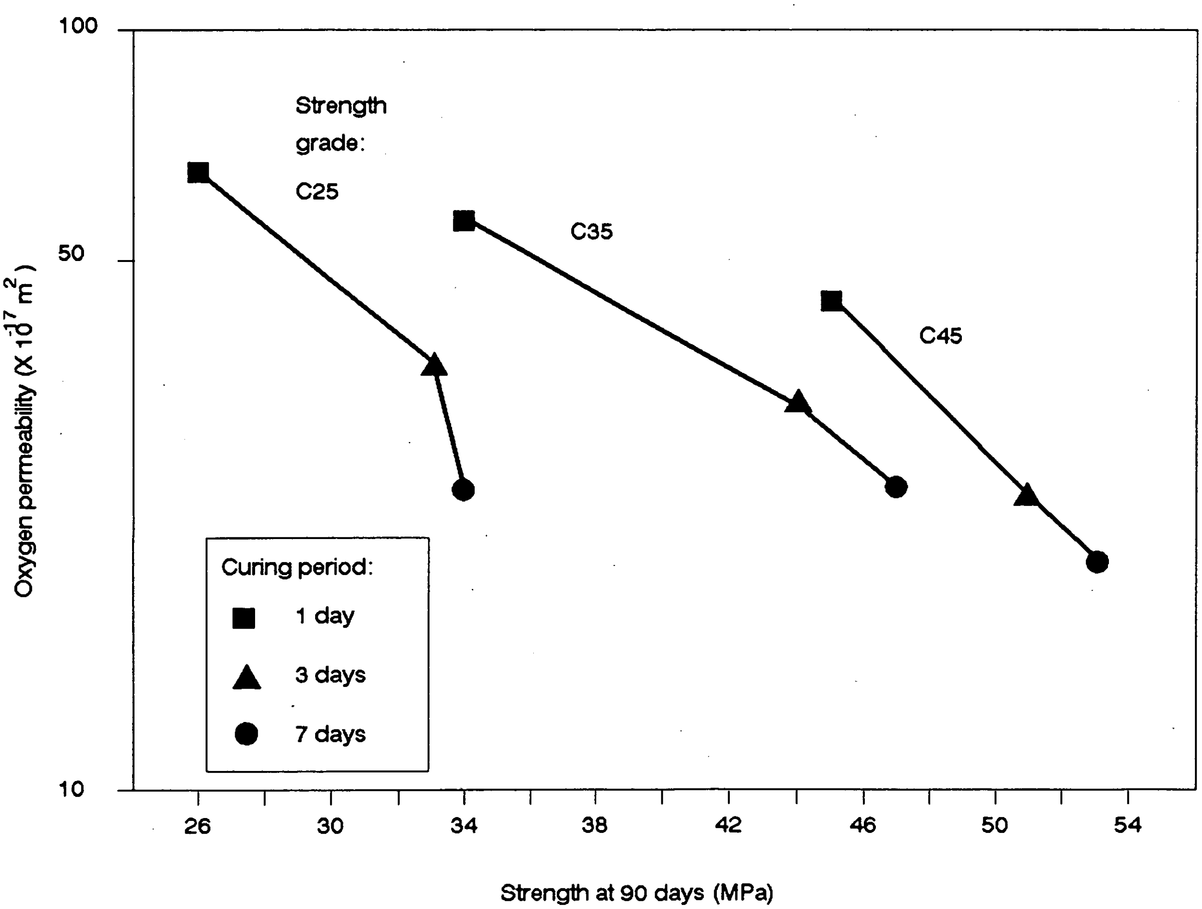

FIGURE 1 Effect of curing on the strength and permeability of opc concrete.

of curing from 1 to 7 days reduced permeability by a factor ranging from 2 (for concrete exposed to high temperature and relative humidity after curing) to more than 9 (for concrete exposed to low temperature and relative humidity).

Generally, fly ash concretes exhibit greater dependence on curing; concretes with higher levels of fly ash had greater reductions in permeability after extended curing. However, fly ash concretes generally were less permeable than opc concrete of the same strength grade, irrespective of the level of curing applied. Similar findings have been reported by others testing gas permeability (*11*), water sorptivity (*11*), and initial surface absorption (*12*). In the present study, low strength concretes (C25) with 50 percent fly ash were less permeable than higher strength concretes (C45) without ash.

The only condition that produces a higher permeability in fly ash concrete than in similar grade opc concrete is inadequate curing, (1 day at 5°C) before exposure to low temperature (5°C) and relative humidity (65 percent relative humidity). If the curing period is extended to 3 days the fly ash concrete is less permeable. The behavior of the concretes at 5°C is interesting. Providing adequate curing was given (3 to 7 days), concretes stored at 5°C are less permeable than comparable specimens stored at 20°C. Although the hydration of portland cement is retarded at low temperature, after sufficient curing periods the quality of concrete is increased because of the improved dispersion of hydration products.

Figure 1 shows the effect of the curing period on both the strength and the permeability of opc concrete. Increasing the initial curing period has a much more pronounced effect on the concrete's permeability than its strength. Ballim (*11*) suggested that increasing the duration of moist curing may be a more efficient way of extending the durability of concrete than increasing the cement content (and design strength). There is no unique relationship between strength and permeability (and hence durability). The relationship is dependent on the level of fly ash replacement, the degree of curing, and the exposure conditions following curing. Consequently, neither design nor in situ strength can be expected to provide a reliable indication of concrete durability. Similar conclusions have been reached by others (*13,14*).

Protection of Steel Reinforcement

Durability of reinforced concrete is controlled largely by the capability of the concrete cover to protect steel reinforcement from corrosion. In hardened concrete, the pH of the pore solution typically is in excess of 13, and at such levels of alkalinity, steel is normally protected from corrosion by a thin surface layer of oxide. However, the steel may become susceptible to corrosion in the presence of chlorides, or if it becomes depassified when the alkalinity of the concrete at the location of the steel is reduced as a result of carbonation. Consequently, it is desirable for the concrete cover to adequately resist penetration of chlorides and carbon dioxide.

Carbonation

Figure 2 indicates the effect of the curing period and storage conditions immediately following curing, on carbonation. Results compiled in Figure 2 and Table 3 indicate that curing has a pronounced

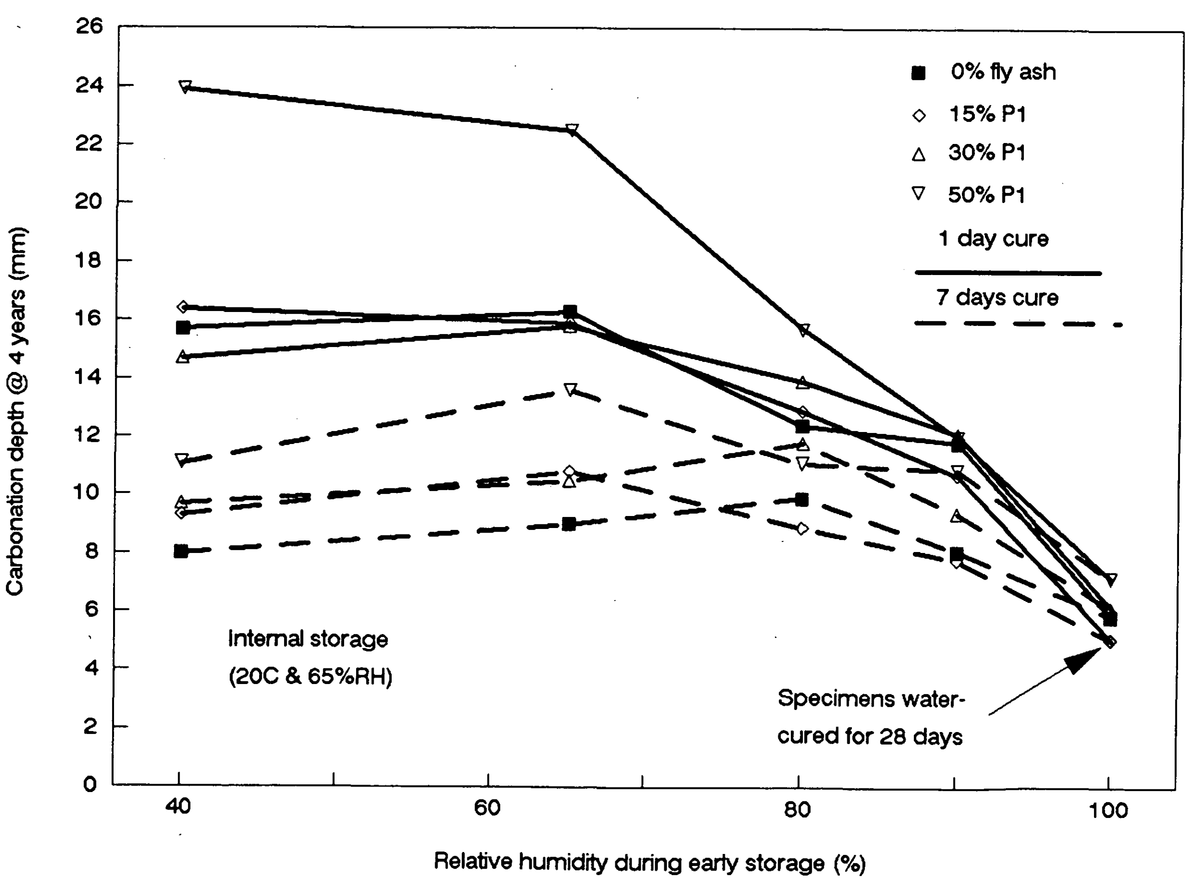

FIGURE 2 Effect of relative humidity during curing on carbonation of concrete.

effect on the carbonation of concrete. Fly ash concretes carbonate at a faster rate than opc concretes of the same strength grade; the effect is more marked at higher replacement levels and under poor curing conditions.

For concretes with a moderate level of fly ash (15 to 30 percent) the differences are small, generally less than 2 mm after 4 years in most cases, compared with the differences resulting from changes in curing or ambient conditions. The results support the view of other researchers (*15–22*) that concretes containing fly ash carbonate to a similar or slightly higher degree compared with opc concrete of the same strength grade, even when the concretes are poorly cured.

At higher levels of fly ash, differences in carbonation rate are more significant, especially for poorly cured lower grade concretes. Increases of more than 12 mm were observed for 25N concretes with 50 percent fly ash compared with equal grade opc concrete stored internally for 4 years.

Figure 3 illustrates the relationship between the carbonation depth of a concrete specimen at 2 years and the actual compressive strength at 28 days of identically cured companion specimens from the same mix. There is a single relationship between these two properties for each exposure environment for all the concrete mixes tested, and the relationships are independent of the level of fly ash and the conditions of curing and early storage.

Carbonation results appear to be in conflict with the permeability results; fly ash concrete carbonates at an increased rate despite being less permeable compared with opc concrete of similar strength (Figure 4). This may be explained by the process of carbonation, which occurs mainly by gaseous diffusion of CO_2, accompanied by chemical interaction between the CO_2 and the cement hydrates, particularly $Ca(OH)_2$. The reduced $Ca(OH)_2$ content of fly ash concrete means that there is less CO_2 consumed; consequently, CO_2 may diffuse more quickly compared with an opc concrete of similar permeability. However, as there is little chemical interaction between oxygen and cement hydrates, permeability to oxygen is a function of the pore structure.

Chloride ion penetration

Table 3 gives chloride diffusion coefficients for concretes cured for 1 day. The coefficients were calculated from chloride concentration profiles after 2-years' exposure, using Crank's solution to Fick's second law (*1*). The duration of initial curing was observed to have little effect on chloride penetration (*1*), and diffusion coefficients calculated from concentration profiles indicated little variation with duration of curing. Those results are in contrast to the permeability and carbonation test results, which show a marked dependence on the initial curing period. The marine-exposed concretes remained in a saturated condition for the duration of the test, and the continued cement hydration and pozzolanic reaction tended to mask the initial differences between specimens because of initial curing conditions. The reduced impact of curing on diffusion results compared with other permeation properties has been observed by others (*23,24*).

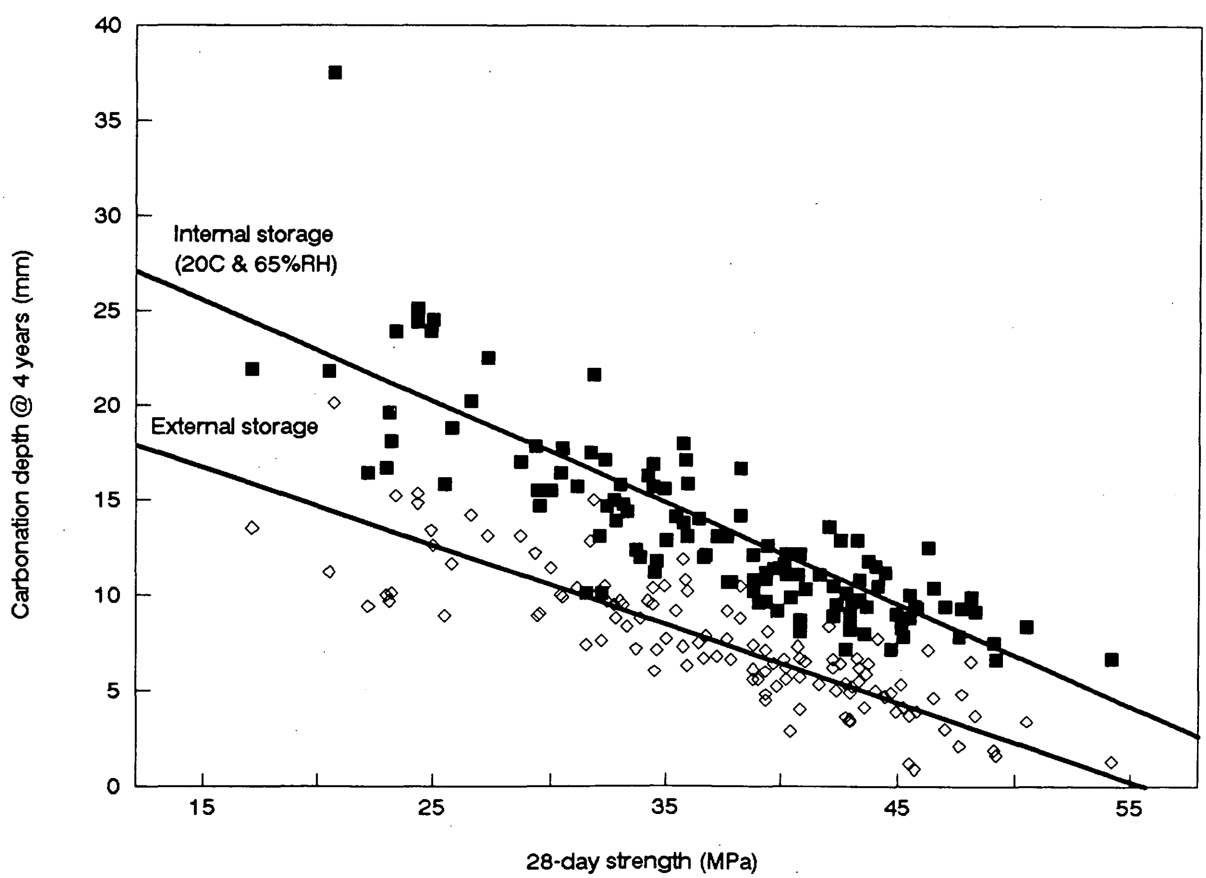

FIGURE 3 Relationship between 28-day strength and carbonation for all concrete mixes.

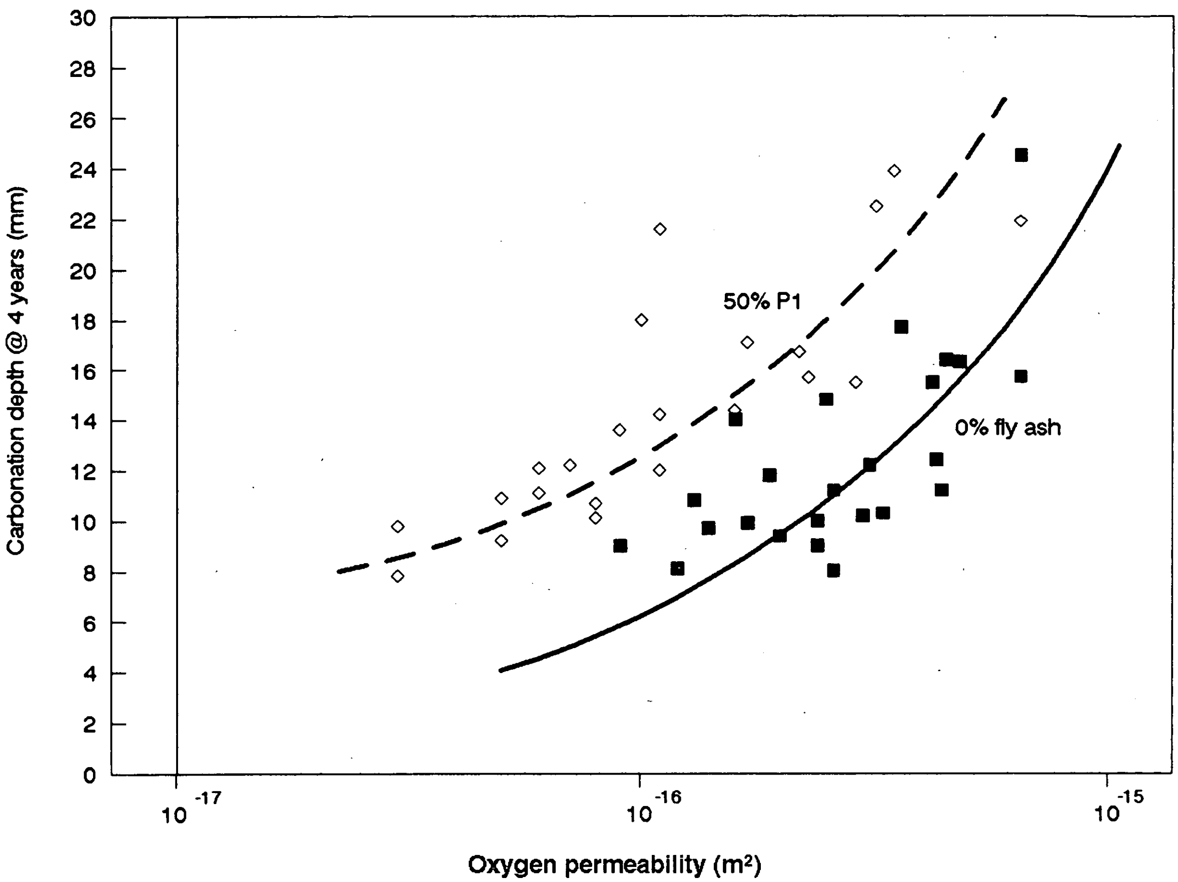

FIGURE 4 Relationship between carbonation and permeability.

In addition to chloride diffusion coefficients, the chloride concentration at depth (26 to 31 mm) is also given in Table 3. The results indicate that the fly ash concrete has a much greater resistance to the penetration of chloride ions than does opc concrete, especially at high replacement levels. Indeed, low grade concretes (C25) with moderate or high levels of fly ash perform better in this environment than (C45) opc concretes.

Figure 5 shows the effect of strength grade and fly ash content on chloride penetration. Increasing the strength or fly ash content reduces chloride penetration. However, increasing the level of fly ash is far more effective; low strength (C25) concretes offer greater resistance than higher strength (C45) opc concrete. Figure 6 shows the change in chloride concentration with time. Differences between fly ash and opc concrete become more marked with time; chloride levels at all depths increase with exposure for opc concretes. The increase in chloride content at a given depth between 1 and 4 years is of the order of 2 times for opc concrete [i.e., the chloride content increases proportionally with the square root of time consistent with Fickean law (*25*)]. In contrast, there is little ingress of chlorides beyond the first year for concretes with high levels of fly ash. A chloride content below 26 mm indicates no significant increase between 1 and 4 years. This finding does not conform with Fickean diffusion, and it has been suggested that the initial profile may be the result of the absorption of chlorides because of the unsaturated condition of the concretes before exposure (*1*). Consequently, the diffusion coefficients for fly ash concretes actually may be lower than those reported in Table 3.

Increased resistance to the penetration of chlorides in fly ash concrete led to substantially reduced corrosion of the reinforcing steel in marine exposed specimens (*1*).

Reduced chloride diffusion of fly ash concretes observed in the present study is consistent with previous studies that have indicated lower diffusion rates for pastes (*26–29*), mortars (*30*), and concretes (*30–34*).

PRACTICAL SIGNIFICANCE OF RESULTS

Curing has a significant influence on the strength and durability of laboratory-size concrete specimens. In practice, only the outer surfaces of larger elements will be affected by early curing, the internal bulk of the concrete will retain its moisture for longer periods (*35*). Consequently, the overall strength of a concrete element may not be adversely affected, and the greater susceptibility of fly ash concrete strength is of practical significance in thin sections exposed to adverse curing environments. Recent studies by the authors (*36*) of fly ash and opc concretes in the field have shown fly ash concrete to invariably have a greater in situ strength than comparable opc concrete (equal design strength or cementitious material content) taken from the same structure. Furthermore, studies of high-volume fly ash concrete structures (up to 56 percent ash), examples of which have existed in the United Kingdom for more than a decade, show these concretes to have strengths considerably in excess of the design strength or measured 28-day strength (*37*).

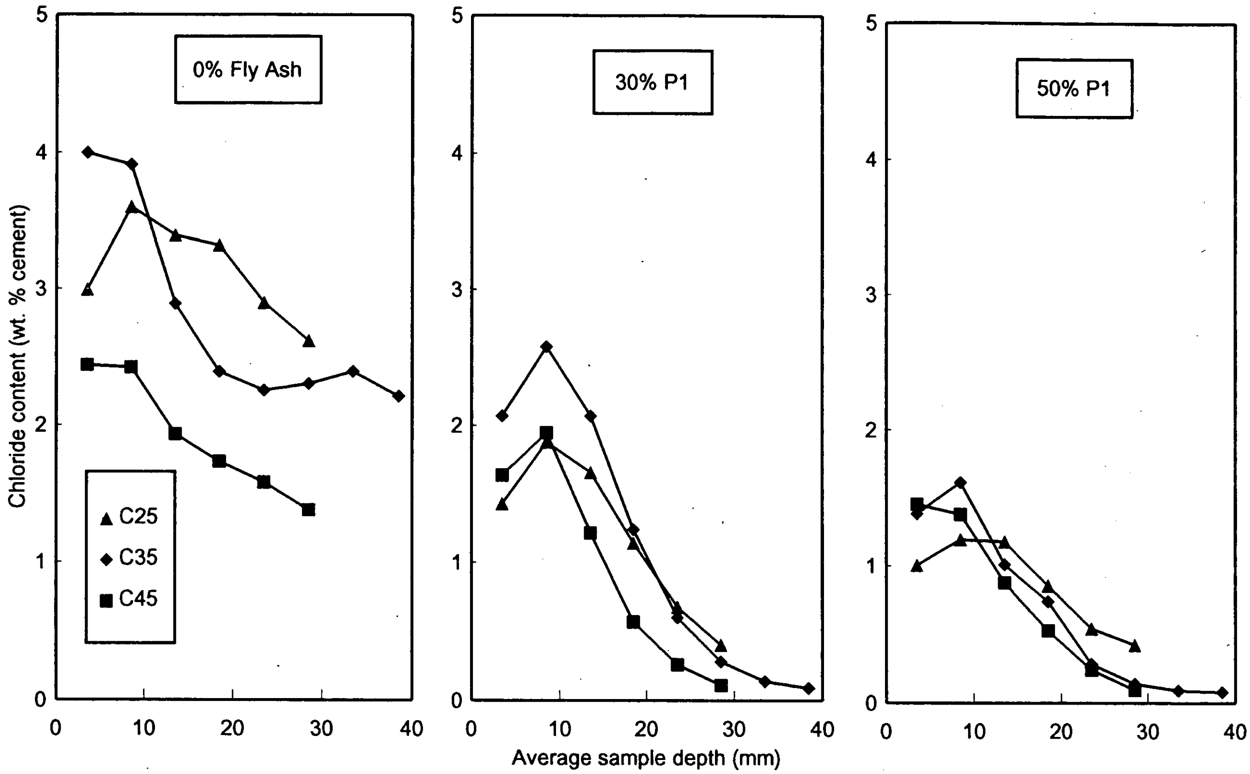

FIGURE 5 Chloride concentration profiles for opc and fly ash concretes after 4 years marine exposure.

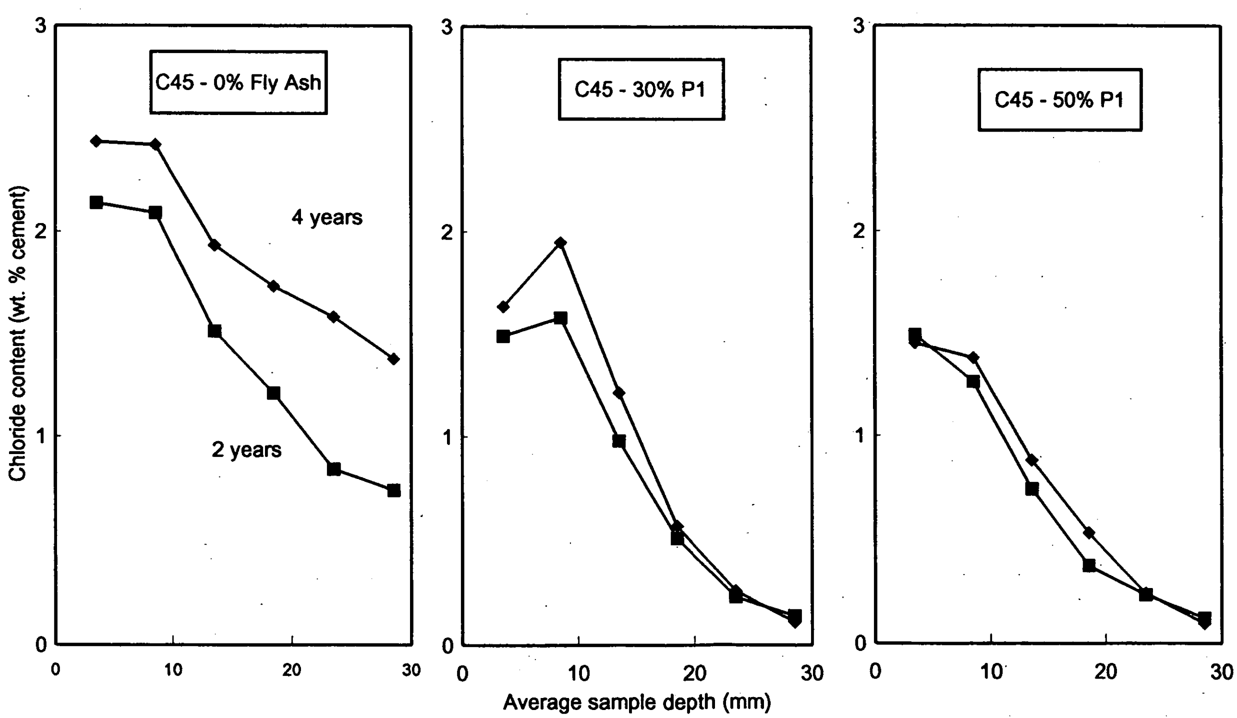

FIGURE 6 Effect of age and fly ash content on chloride concentration profiles in concrete.

Properties of the outer surfaces or "covercrete" of concrete elements have a major influence on the durability of the structure, as such surfaces provide protection to the steel reinforcement and bulk concrete. The results of this study indicate that fly ash concrete may be less permeable and considerably more resistant to the penetration of chloride ions than opc concrete of the same strength grade, irrespective of the level of curing provided. Differences in carbonation depths were not marked for concretes with fly ash contents between 0 and 30 percent. The results correlate well with field studies (*36*), which show fly ash concrete to be less permeable and more resistant to the penetration of chlorides from deicing salts or seawater than is comparable opc concrete with the same exposure. Fly ash concretes in the field exhibit slightly higher carbonation also. Overall, the results indicate that concretes with normal levels of fly ash (15 to 30 percent require no additional curing, as compared with opc concretes of the same strength grade.

High fly ash content concretes (50 percent) show excellent durability properties, for increased carbonation rates. The differences can be significant under certain curing and exposure conditions, so particular attention should be paid to the curing fly ash concretes if the design of the structure and conditions of exposure are conducive to carbonation.

All the concretes studied had improved durability when the curing period was extended. The importance of providing adequate curing protection cannot be overemphasized. Although, inadequate curing may be compensated for by decreasing the water to cementitious material ratio of the concrete, this will usually result in higher cement contents and concomitant increases in shrinkage, hydration temperature, alkali contents, and material costs.

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