The Use of High-Volume Fly Ash in Concrete

M.D.A. Thomas, D.S. Hopkins, G. Girn, R. Munro and E. Muhl

Synopsis: This paper discusses the use of high-volume fly ash as a cementitious component in concrete and its contribution to enhancing the sustainability of concrete construction. Fly ash is an industrial by-product and, as such, represents a material that embodies little energy in its production. Furthermore, its use meets other environmental needs as it reduces the use of Portland cement and results in a concrete with increased durability. Fly ash has a long history of use in concrete construction, however, it is normally used to partially replace Portland cement at relatively modest levels of between 15 to 25% (by mass). The use of higher replacement levels (e.g. ≥ 50%) requires special consideration especially in environments where concrete is required to provide protection to embedded steel. This paper presents data from durability studies of concretes containing up to 60% fly ash; studies include carbonation, chloride resistance, permeability and strength. Data are also presented from a recent construction project in Toronto where high-volume fly ash concrete was used as part of a "Green Building Strategy". Finally, the paper presents recent data from studies using ternary blends of cement with high levels of fly ash (e.g. 56%) and small levels of silica fume (3 to 4%). It is shown that the poor early-age performance that may be associated with high-volume fly ash can be offset by the inclusion of silica fume.

Keywords: carbonation, chlorides, concrete, durability, high-volume fly ash, permeability, silica fume, strength, ternary blends

Michael Thomas is a professor in the Department of Civil Engineering at the University of Toronto.

Don Hopkins, P.Eng., is Director, Marketing Communications, Canadian Cement Operations for Lafarge Canada Inc.

Gurinder S. Girn, P.Eng., is the Cementitous Materials Manager for the Eastern Region of Lafarge Canada Inc.

Robert Munro is the Technical Services Manager for the Ontario Region of Lafarge Canada Inc.

Emese Muhl is a graduate student in the Department of Civil Engineering at the University of Toronto.

INTRODUCTION

Fly ash, a by-product of burning pulverized coal in thermal generating stations, is a finely-divided, amorphous alumino-silicate that reacts at normal temperature with calcium hydroxide to produce calcium-silicate hydrates (C-S-H) with cementitious properties; i.e. it is a pozzolanic material. As such, fly ash is a valuable resource to the construction industry as it can be used together with Portland cement to produce concrete. Fly ash will react with the calcium hydroxide liberated by the normal hydration of Portland cement producing additional cementitious material in the hardened concrete. The potential for using fly ash in this manner has been known almost since the start of the last century (1) although it wasn't until the mid-1900's that significant utilization of fly ash in concrete began (e.g. ref. 2). The last 50 years has seen the use of fly ash in concrete grow dramatically with current usage in the United States being somewhere in excess of 6 million tonnes per annum (3). This increased usage has been accompanied by a great deal of applied and fundamental research culminating in many thousands of technical papers providing testament to the fact that the appropriate use of fly ash in concrete can result in numerous technical and economic benefits. Despite this, the use of fly ash is often restricted by concrete specifications, either by total prohibition or by limiting the amount that can be used. A good example of this is the ACI Building Code (ACI 318), which limits the amount of fly ash to a maximum of 25% by mass of the total cementitious material.

Many workers have demonstrated that fly ash can be used at much higher replacement levels (e.g. > 40%) to produce concrete with good mechanical properties and excellent durability. One example of note, is the work of CANMET in developing a specific type of "high-volume fly ash concrete", which is characterized by the incorporation of high fly ash contents (typically ~ 56%) and large dosages of superplasticizer to achieve exceptionally low water-cementitious material ratios (typically W/CM ~ 0.32).

Although the use of high levels of fly ash has generally been restricted to special applications such as roller-compacted concrete or large monolithic pours requiring temperature control, it has been demonstrated that levels of between 40 to 60% fly ash can be successfully used in normal structural concrete (5). However, it should be noted that concrete with high levels of fly ash displays different characteristics than plain Portland cement concrete and may require special consideration (e.g. with regard to curing and early-age strength development), especially when used at low ambient temperatures. It is perhaps for this reason that specifications (e.g. ACI 318) have been reluctant to permit higher levels of fly ash to be used for general concreting purposes. This is a pity since concrete properly produced with high levels of fly ash can have many technical advantages over normal concrete, particularly with regards to long-term durability in certain environments. Furthermore, the use of high levels of fly ash is beneficial in environmental terms as it utilizes an industrial by-product and results in reduced consumption of Portland cement.

This paper reports data from a long-term study of concrete containing up to 50% fly ash and more recent data from studies on concrete containing high volumes of fly ash (e.g. up to 56%) in conjunction with silica fume. Furthermore, an example is presented on the very recent use of concrete with 50% fly ash in a building in the Greater Toronto Area. In this case, the fly ash was used solely to meet the environmental policy of the building, but it is argued that fly ash could be used in a similar manner in routine construction to both economic and environmental benefit.

STUDIES AT BRE

A research program was initiated at the Building Research Establishment (BRE) in the U.K. in 1986 to examine the effects of curing on the strength and durability of concrete containing fly ash. Much of the data from this study has been published in a series of technical papers (6-10) although long-term data are still being collected from marine exposure conditions. Some of these data are re-examined here to specifically evaluate the performance of the concretes containing high volumes of fly ash (50%). In this program three series of concrete mixtures, of nominal strength grades 25, 35 and 45 MPa (designated C25, C35 and C45, respectively), and with slump values in the range 30 to 60 mm, were designed using a range of fly ash levels (0 to 50 % by mass). In order to achieve strength parity (cube strength after 28 days in water at 20°C) at a particular strength grade, a cementing efficiency factor, $k = 0.3$, was used such that the "free" water - "effective" cementitious material ratio, $W/(C + kF)$, remained constant within a given series. Advantage was taken of the improved workability of fly ash concrete and the mixing water was reduced with increasing ash content (approximately 3% water for each 10% ash). The chemical analysis of the cement and fly ash are given in Table 1 and the details of concrete mixtures are presented in Table 2.

Examination of the data in Table 2 shows that equivalent strength at 28 days can be achieved using 50% fly ash by increasing the total cementitious content (Portland cement + fly ash) by 30% and reducing the water content by 15% compared with plain Portland cement concrete. This results in the fly ash concrete mixtures having 35% less Portland cement than the equivalent strength mixture without fly ash. Naturally, this leads to the fly ash mixtures having a significantly lower water to cementitious materials ratio for a given strength grade. However, equal strength and workability was chosen as the basis for comparison in this study since these parameters are generally those used when specifying and ordering concrete in the U.K.

The data presented here are for concretes cast at either 5^oC or 20^oC and then cured at the same temperature for either 1, 3 or 7 days (including the 1 day spent in the moulds). After curing the specimens were stored in air at the same temperature (i.e. 5^oC or 20^oC) and 65% relative humidity until they were 28 days old. At 28 days, concretes were tested for strength, placed in the tidal zone of BRE's marine exposure site (10), stored in various conditions to determine the rate of carbonation (9), or subjected to permeability testing. The oxygen permeability data presented here are for specimens that were "conditioned" for a further 28 days at 20^oC and 65% (i.e. they were 56 days old at the time of test) before being tested in a permeability rig described in detail elsewhere (7).

Figure 1 shows the effect of the duration of moist curing on the 28-day strength of concretes from the C25 and C45 mixtures (the data for the C35 concretes generally fell between these data and have been excluded from the figure for clarity). For specimens cured for 3 days or more there is clearly little difference between the strength of concrete with no fly ash or 50% fly ash. However, the strength of concrete with 50% fly ash was significantly lower than the control mixture when the duration of curing was reduced to just 1 day. The effects of moist curing became more pronounced for concretes cured at 5^oC as shown in Figure 2 for specimens from the C35 concretes. The concrete with 50% fly ash achieved only 50% of its 28-day water-cured strength when it was subjected to 1 day moist curing at a temperature of 5^oC.

Figures 3 and 4 show similar comparisons for the permeability data. For specimens cured at 20^oC (Figure 3), the permeability of fly ash concrete was significantly lower than equivalent grade concrete without fly ash. The improvements attributed to the fly ash become more significant as the period of moist curing increases and as the strength grade of the concrete increases. When the curing temperature was reduced to 5^oC the permeability of the fly ash concrete was observed to increase and there was little difference between the fly ash and control concrete. The permeability of the concrete is clearly more sensitive to the duration of the moist curing period when curing is carried out at lower temperatures.

Figure 5 shows the depth of carbonation at 4 years for concretes stored outdoors with protection from direct precipitation. This exposure condition is felt to be the most relevant for predicting the service life of reinforced concretes subjected to carbonation-induced corrosion (9). Carbonation rates may be higher for specimens stored indoors (e.g. at constant 65% relative humidity), but such conditions are not conducive to steel corrosion. It is very apparent that concrete containing 50% fly ash carbonates at a significantly faster rate than equivalent grade concrete without fly ash and that the difference in performance is more marked in poorly-cured concretes of low strength grade. Surprisingly differences between the concretes with and without fly ash do not seem to be exacerbated by low temperature curing (Figure 6).

Figures 7 and 8 show chloride concentration profiles established for C35 concretes after exposure in a marine tidal zone for 1 and 10 years, respectively. The duration and temperature of the moist curing period was found to have little effect on the extent of chloride penetration after ages of 1 year (8,10). The resistance to chloride penetration increases significantly as the fly ash content of the concrete increases. Figure 9 compares 10-year data for the three different grades of concrete without fly ash and with 50% fly ash. The C25 concrete with 50% fly ash shows far superior performance to the higher strength C45 concrete without fly ash. These concretes have similar water to cementitious materials ratios; for the C25 mixture with 50% fly ash W/CM = 0.44 and for the C45 mixture without fly ash W/CM = 0.49.

STUDIES ON TERNARY BLENDS AT THE UNIVERSITY OF TORONTO

This study was carried out to evaluate the use of ternary cementitious blends, consisting of Portland cement + silica fume + fly ash, on the properties of high performance concrete. Complete details of the experimental program and early-age (up to 180 days) data have been presented elsewhere (11). All concretes were cast with blended silica fume cement (CSA Type 10 Portland cement interground with 8% pelletized silica fume – designated as Type 10SF in Canada) with fly ash contents of 0, 25, 40 and 56%. Three different fly ashes were used in the original program and these were representative of the three classes of fly ash currently recognized by CSA A23.5 (i.e. Type F, Type CI and Type CH). Only data for the fly ash with the intermediate calcium content (i.e. Type CI) are presented here. The chemical composition of the blended cement (Type 10SF) and the Type CI fly ash are given in Table 1.

Mixtures were designed with low water to cementitious ratio and nominally similar dosages of water reducer (175 to 195 ml/100 kg of cementitious material) and superplasticizer (200 to 250 ml/100 kg). The cementitious contents and water contents were designed in an attempt to achieve similar slump and 28-day strength. The target mixture proportions are given in Table 3. Unfortunately, due to a clerical error the mixtures with 25% fly ash were batched with a unit water content of 120 kg/m^3 instead of 130 kg/m^3, resulting in a water to cementitious materials ratio of 0.24 instead of the target W/CM = 0.26. All mixtures were air entrained, however, the measured air contents were low, being in the range of 4.0 to 4.8%.

Compressive strength results are given in Table 4. The 28-day strengths of standard-cured samples were comparable between the different concretes despite the errors made in the water content of the mixture with 25% fly ash. However, the lower water content in these mixtures did lead to lower slumps (11). At early ages (1 and 3 days) the compressive strengths of the concretes with fly ash were lower than the mixture with just Type 10SF cement, especially at the higher levels of fly ash. However, after 7 days all concretes achieved strengths in excess of 40 MPa and the differences between concretes were small. Table 4 also shows strength results for concretes that were subjected to a temperature cycle during the first 3 days. This involved placing freshly cast specimens over water in sealed containers and raising the temperature at a steady rate to achieve 60°C at 24 hours (approx. 1.5°C/hour). The temperature was held at 60°C for a further day and then allowed to cool to room temperature over a period of 24 hours. This cycle was intended to replicate a typical autogenous temperature cycle in a thick element. The data in Table 4 show that the temperature cycle was extremely beneficial to the concrete containing fly ash, the strengths of concretes with 25% and 56% fly ash being higher than the Type 10SF control concretes at all ages. The strength of the concrete with 40% fly ash exceeded that of the concrete without fly ash at 182 days, but was slightly lower at earlier ages.

Durability testing of these concretes has included water permeability and chloride diffusion testing using a variety of test methods. However, the data presented here will be restricted to results from ASTM C 1202 testing. This test has become known as the “rapid chloride permeability test” or “RCPT” although the test actually measures electrical conductivity rather than permeability. Figure 10 shows the RCPT data at four different ages between 28 days and 4.5 years. All the measured conductivities were very low at 28 days, falling within the range 130 to 250 coulombs. However, with extended curing there was little change in the conductivity of the concrete without fly ash, but a steady and continuous decrease was observed for the mixtures with the Type 10SF cement plus fly ash, the extent of the decrease being greatest for the concrete with the higher level of fly ash (56%). Indeed, on one occasion a sample of the concrete with 56% fly ash actually registered a reading of zero charge passed after 6 hours of testing. Long-term bulk diffusion testing, the results of which will be reported in detail at a later date, indicate that the fly ash concretes essentially become "impenetrable" to chloride ions at later ages.

Figure 11 shows RCPT data from another study at the University of Toronto. These mixtures contained varying levels of fly ash combined with plain Portland cement (i.e. without silica fume). Only the data for the control concrete and the concrete with 56% fly ash are shown here for the purpose of demonstrating the impact of maturity on the properties of concrete with high levels of fly ash. At the age of 28 days there is little difference in the conductivity of concrete with and without fly ash and values in excess of 1000 coulombs were recorded even at the lowest water to cementitious material ratio used (i.e. W/CM = 0.35). However, after extended curing concrete with 56% develops a very low electrical conductivity whereas comparatively little change occurs for concrete without fly ash.

USE OF HIGH VOLUME FLY ASH CONCRETE AT YORK UNIVERSITY

Part of the "Green Building Strategy" of a recent construction project at York University in Toronto, included the use of "Green Products". Such products were defined as those with one or more of the following characteristics: (i) embodying low energy costs, (ii) being of high durability and low maintenance, (iii) containing a large proportion of recycled or recyclable materials. Consistent with this philosophy was the decision to use high contents of fly ash as a cementitious material in the concrete components of the building.

The specified strength of the concrete used was 30 MPa for columns, walls and suspended slabs and 25 MPa for the lower slab-on-grade. The maximum water to cementitious ratio was 0.45 (for the 30-MPa concrete) and the specification called for a minimum of 7 days moist curing. Mixture proportions for the job concretes are given in Table 5. Both concretes contained 50% fly ash by mass of cementitious material; the fly ash used was Northern Ash, which is a blend of fly ash from the Thunder Bay and Atikokan Generating Stations in Northern Ontario. A typical chemical analysis of this fly ash is given in Table 1. The use of 50% fly ash in the concrete allowed a 40-kg/m^3 reduction in the water content of the concrete compared to an equivalent Portland cement concrete mixture produced with the same materials and with the same dose of water-reducing admixture. For the 30-MPa concrete, this could have permitted a 90-kg/m^3 decrease in the cementitious material content whilst maintaining the specified W/CM at 0.45. However, the producer opted to supply the concrete at a lower W/CM in the range of 0.38 to 0.40. The average strengths at 7 and 28 days were 36 and 45 MPa, respectively, with slightly higher strengths being achieved when a retarder was added during periods when the ambient temperature was high. Slump values were generally in the range of 80 to 100 mm.

Field samples were cast from this mixture and a comparable (i.e. nominally 30-MPa) plain Portland cement mixture for durability testing in the laboratory. This mix had a cementitious materials content of 340 kg/m^3, which was comprised of 100% Type 10 Portland cement, and a

W/CM of approximately 0.45. Strength data for these field- produced mixtures are shown in Figure 12. The mix with 50% fly ash shows reduced early-age strength compared with the control, but the strength at 28 days and later is greater. Concrete slabs were delivered to the University of Toronto at an age of 1 day and these slabs were either given no further curing or were stored in the fog room for an additional 2 or 6 days to provide a total moist-curing period of 1, 3 or 7 days. These slabs were then stored in the laboratory until test. The testing carried out includes a whole suite of tests aimed at characterizing the pore structure of the concrete and its permeability to vapour, fluid and ionic transport. Only data from the "rapid chloride permeability test" are reported here, and these were as follows (specimens approximately 6 months old at the time of test):

	RCPT (Coulombs)	
Curing Period	Control (30-MPa)	50% Fly Ash
1 day	4044	878
3 days	3168	522
7 days	2790	320

The charge passed in this test indicates that the fly ash concrete has a much lower permeability than the control concrete and that the differences become more marked with curing. It should be noted that in addition to the presence of fly ash, these two mixtures differed in terms of W/CM and the unit water content of the mix.

DISCUSSION

The data presented here from various studies indicate that concrete with high levels of fly ash (≥ 50% by mass of cementitious material) can be produced to have a high strength and good durability (as characterized by permeability and resistance to chloride ion penetration). Other studies have shown high volume fly ash concrete to possess good resistance to alkali-silica reaction and sulphate attack. However, high volume fly ash concrete is a different material to normal cement concrete and this needs to be considered when designing and producing material with high contents of ash. Particular attention should be paid to curing such concrete as both the strength and permeability are strongly influenced by the duration of moist curing.

Poorly cured, low strength concrete with high levels of fly ash may carbonate very rapidly under certain exposure conditions. Tests at BRE indicate that 25-MPa concrete with 50% fly ash may carbonate by 20 mm after just 4 years' outdoor exposure if no further moist curing is applied after stripping the concrete at 24 hours. At such a rate, the carbonation front might be expected to reach embedded steel with 40 mm of concrete cover after only 16 years (assuming a square-root time relationship). There exists a perception that corrosion of reinforcing steel due to carbonation is not a problem in North America. This is probably due to the fact that moderate-strength Portland cement concrete has a fairly high resistance to the penetration of CO_2 and will generally provide satisfactory protection to the steel (in non-chloride environments) provided adequate cover is present. The same degree of protection can be achieved with high volume fly ash concrete but this requires the use of a higher strength grade (lower W/CM) material with more attention being paid to the initial curing period. If high levels of fly ash are used in general concreting work without adopting these measures then, in the authors' opinion, problems due carbonation-induced corrosion will eventually be manifested.

The use of high fly ash contents may be appropriate for a wide range of concrete applications although, for the reasons stated above, modifications to the durability requirements of codes and standards may be necessary to ensure satisfactory long-term performance. For example, in Canada the national specification covering concrete construction (CSA A23.1) requires a minimum strength of 25 MPa and a maximum W/CM of 0.55 for an F-2 exposure (concrete in an unsaturated condition exposed to freezing and thawing, but not to chlorides). The minimum specified curing period is 3 days and the minimum depth of cover is 40 mm for such concrete. These limits may not be sufficiently onerous for concrete containing high contents of fly ash. In the authors' opinion reinforced concrete containing 50% or more fly ash should not be produced with a water-to-cementitious-materials ratio above 0.40 if long-term durability is required. Indeed, if adequate curing cannot be guaranteed even lower water to cementitious materials ratios may be appropriate.

On the other hand, in chloride environments high volume fly ash concrete is likely to provide much enhanced protection to the steel compared to Portland cement concrete of the same strength grade or even of the same W/CM. However, curing is again important if the full benefits of incorporating the fly ash are to be realized.

The performance (strength and permeability) of high volume fly ash concrete at early ages can be greatly enhanced by the use of relatively small levels of silica fume (or perhaps other highly reactive pozzolans). Concrete containing 3.5% silica fume and 56% fly ash exhibited a very high resistance to chloride ion penetration and reasonable strengths at early ages. Other studies have shown concretes with blends of silica fume and fly ash to have other excellent properties also (12).

The potential for using higher levels of fly ash than those currently used in normal concrete construction is enormous. Providing sensible precautions are taken, the incorporation of 50% or more fly ash in concrete can result in both technical and economic benefits. With experience it is possible for producers to proportion high volume fly ash mixtures to produce concretes with a wide range of properties (e.g. strength and slump) thereby meeting the requirements for most routine concrete applications. There really is no compelling reason why concrete mixtures with 50% fly ash shouldn't be used for applications ranging from residential foundations to highway structures provided the designer, producer and contractor are cognizant of the different requirements when such a material is used. Indeed, there are many good reasons why high volume fly ash concrete should be used.

On a final note, it should be stated that fly ashes vary widely in composition and hence to the degree that they affect the properties of concrete. It is not possible to take a single approach to designing concrete mixtures; producers have to gain experience with individual fly ashes and how they interact with the materials (cement, aggregates and admixtures) within a given plant. For example, the cementing efficiency approach used in designing the BRE mixtures, using k = 0.3, is clearly not applicable for the materials used for the building at York University. The Northern Ash used for this project clearly has a much larger water-reducing effect than the fly ash used in the BRE study. This may be due to the combined action of the fly ash and the water-reducer in the concrete used at York University. Furthermore, much smaller reductions in the W/CM were required to achieve equivalent strength when 50% Northern Ash was used. In fact, the cementing efficiency factor for this fly ash is somewhere in the region of k = 0.8. This is probably due to the increased reactivity of the Northern Ash on account of its relatively high calcium and alkali contents compared with the BRE fly ash. The cementing efficiency concept is not really practical in North America where the composition of the fly ashes available varies so widely.

CONCLUSIONS

1. High-volume fly ash is more sensitive to the duration of moist curing than Portland cement concrete, especially at low ambient temperatures.
2. Poorly cured, low strength grade (e.g. 25 MPa) concrete with 50% fly ash carbonates very rapidly when stored outdoors sheltered from direct precipitation.
3. Although high volume fly ash concrete is likely to be suitable for many applications, existing limits in codes and standards may not be sufficient to ensure satisfactory long-term performance in some exposure conditions (mainly because of the risk of carbonation).
4. High-volume fly ash concrete has a very high resistance to chloride penetration almost regardless of the strength grade, however, adequate curing is required to achieve the full benefits of the fly ash.
5. The performance of high volume fly ash concrete, especially at early ages, can be greatly enhanced by incorporating relatively small proportions of silica fume.

REFERENCES

1. Anon. "An investigation of the pozzolanic nature of coal ashes." Engineering News, Vol. 71, No. 24, 1914, pp 1334-1335.
2. Bureau of Reclamation. Physical and Chemical Properties of Fly Ash - Hungry Horse Dam. Laboratory Report CH-95, U.S. Bureau of Reclamation, 1948.
3. Manz, O.E. "Worldwide production of coal ash and utilization in concrete and other products." In Proceedings of the 10th International Ash Use Symposium, Volume 2, EPRI TR-101774, Vol. 2, Electric Power Research Institute, 1993, pp 64/1-12.
4. Malhotra, V.M. “CANMET investigations dealing with high-volume fly ash concrete.” Advances in Concrete Technology, 2nd Edition, CANMET, Ottawa, 1994, pp. 445-482.
5. Dunstan, M.R.H., Thomas, M.D.A., Cripwell, J.B. and Harrison, D.J. “Investigation into the long-term in-situ performance of high fly ash content concrete used for structural applications.” Proceedings of the 4th International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete (Ed. V.M. Malhotra), ACI SP-132, Vol. 1, American Concrete Institute, Detroit, 1992, pp. 1-20.
6. Thomas, M.D.A. and Matthews, J.D. "Carbonation of fly ash concrete." Magazine of Concrete Research, Vol. 44, No. 158, 1992, pp 217-228.

7. Thomas, M.D.A. and Matthews J.D. "The permeability of fly ash concrete." Materials and Structures, Vol. 25, 1992, pp 388-396.
8. Thomas, M.D.A. "Marine performance of pfa concrete." Magazine of Concrete Research, Vol. 43, No. 156, 1991, pp 171-185.
9. Thomas, M.D.A. and Matthews, J.D. "Carbonation of fly ash concrete." Proceedings of the 4th ACI/CANMET International Conference on the Durability of Concrete (Ed. V.M. Malhotra), ACI SP-192, Vol. 1, American Concrete Institute, Detroit, 2000, pp. 539-556.
10. Thomas, MDA and Matthews, JD. 1996. "Chloride penetration and reinforcement corrosion in marine-exposed fly ash concretes." Third CANMET/ACI International Conference on Concrete in a Marine Environment (Ed. V.M. Malhotra), ACI SP-164, American Concrete Institute, Detroit, 1996, pp. 317-338.
11. Thomas, M.D.A. and Evans, C.M. "Chloride penetration in high-performance concrete containing silica fume and fly ash." Second International Conference on Concrete Under Severe Conditions - CONSEC '98, Tromso, Norway, June, 1998.
12. Thomas, M.D.A., Shehata, M.H., Shashiprakash, S.G., Hopkins, D.S. and Cail, K. "Use of ternary cementitious systems containing silica fume and fly ash in concrete." Cement and Concrete Research, Vol. 29, 1999, pp. 1207-1214.

Table 1 Analysis of Cement and Fly Ashes

Oxide	BRE Program		U of T		Northern Fly Ash
	OPC	Fly Ash	T10SF	Fly Ash	
SiO_2	20.6	48.2	26.8	54.2	45.4
Al_2O_3	5.07	26.7	4.07	22.0	20.2
Fe_2O_3	3.10	11.6	3.11	3.95	4.31
CaO	64.5	1.71	57.8	12.4	13.7
MgO	1.53	1.62	2.76	1.12	2.86
K_2O	0.73	3.18	2.76	0.21	0.59
Na_2O	0.15	0.65	0.18	2.73	6.79
SO_3	2.53	0.83	0.94	0.29	1.48
LOI	1.58	4.34	-	0.26	0.59
<45µ	-	11.3	-	-	-

Table 2 Details of Concrete Mixtures for BRE Program

Nominal strength grade	Fly Ash content (%)	Cement (C+F) (kg/m^3)	W/CM	Slump (mm)	28-day cube strength (MPa)
C25	-	250	0.68	60	32.5
	50	324	0.44	40	33.0
C35	-	300	0.57	50	41.5
	50	392	0.37	30	41.5
C45	-	350	0.49	40	50.0
	50	452	0.32	30	48.0

Table 3 Target Mixture Proportions –Ternary Blend Study

	Mixture Proportions (kg/m^3)			W/CM
	T10SF	Fly Ash	Water	
Control	450	-	135	0.30
25% FA	375	125	130	0.26
40% FA	330	220	130	0.24
56% FA	242	308	130	0.24

Table 4 Strength of Concretes with Ternary Blends (MPa)

	Fly Ash (%)			
	0	25	40	56
Ambient-temperature-cured concretes				
1 day	27.8	26.2	18.1	10.0
3 days	41.4	33.5	30.1	26.9
7 days	46.1	43.5	42.6	41.6
28 days	**61.6**	**59.2**	**60.4**	**57.7**
182 days	69.6	60.9	62.1	64.5
Oven-cured concretes				
3 days	47	56.9	41.8	56.3
7 days	50.2	58.1	43.7	57.2
28 days	**53.7**	**58.3**	**49.8**	**58.6**
182 days	54.8	60.2	55.7	63.7

Table 5 Details of Concrete Mixtures for York University

		25-MPa	30-MPa
Type 10 cement (kg/m^3)		150	170
Thunder Bay fly ash (kg/m^3)		150	170
Stone (kg/m^3)		1150	1110
Sand (kg/m^3)		850	800
Water (kg/m^3)		135	135
W/C		0.45	0.40
Slump	No. of Tests	15	49
	Mean (mm)	101	89
	S.D. (mm)	21	21
28-day Strength	No. of Tests	8	20
	Mean (MPa)	32.4	44.5
	S.D. (MPa)	3.6	3.8

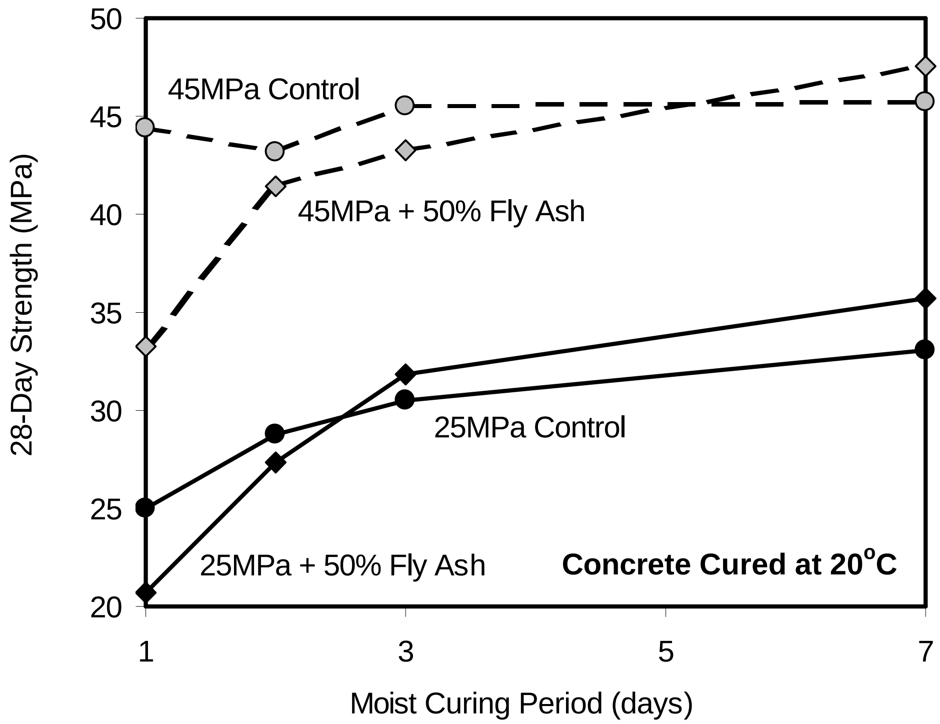

Fig. 1 Effect of Curing on Strength of Concrete Cured at 20°C

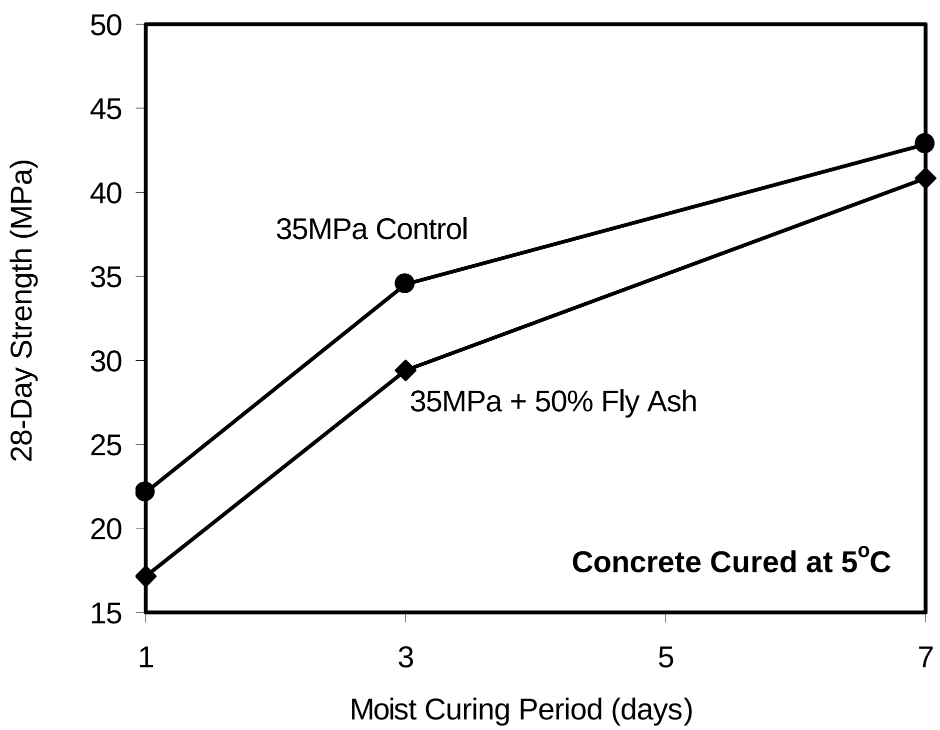

Fig. 2 Effect of Curing on Strength of Concrete Cured at 5°C

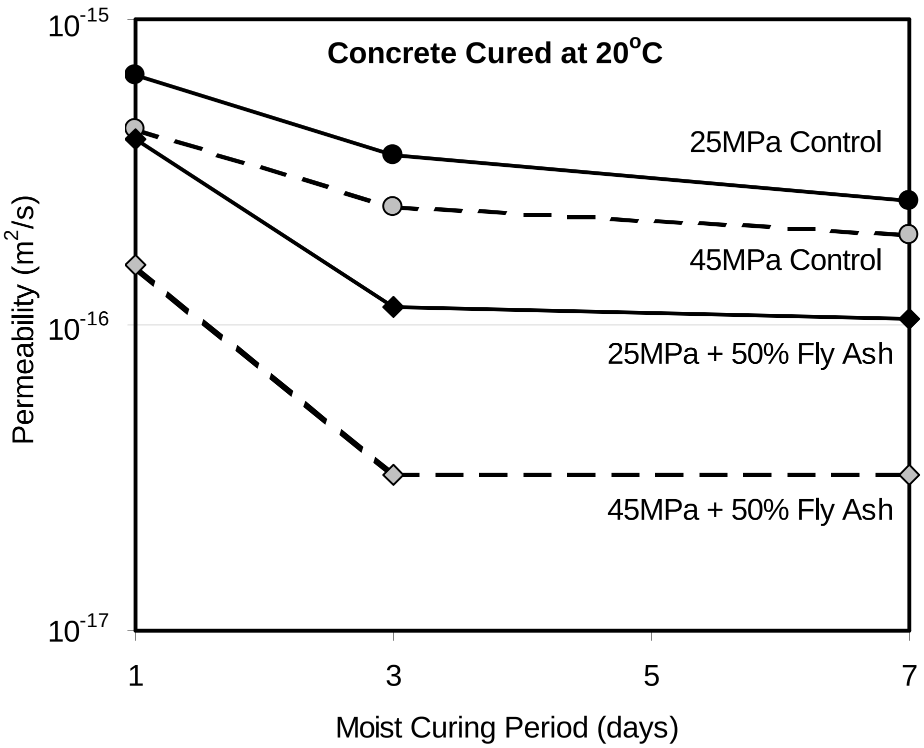

Fig. 3 Effect of Curing on Permeability of Concrete Cured at 20°C

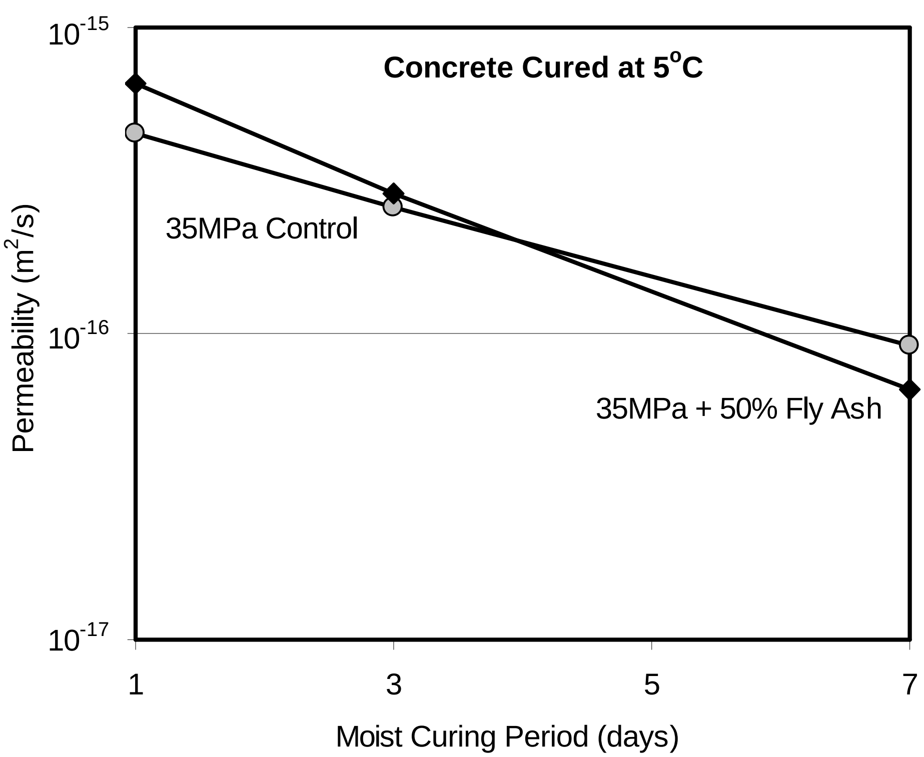

Fig. 4 Effect of Curing on Permeability of Concrete Cured at 5°C

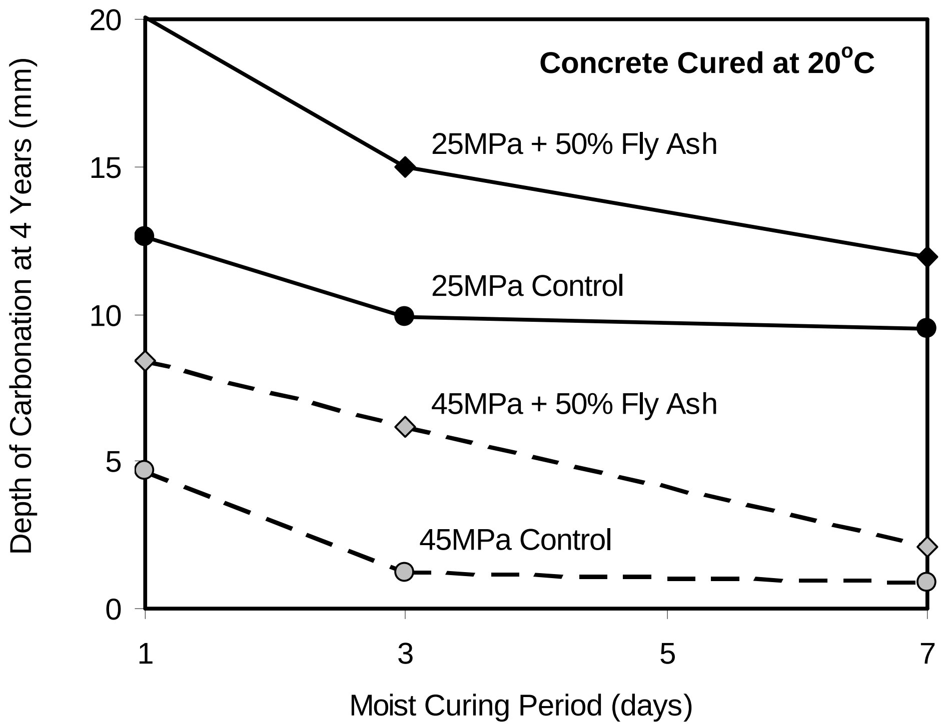

Fig. 5 Effect of Curing on Carbonation of Concrete Cured at 20°C

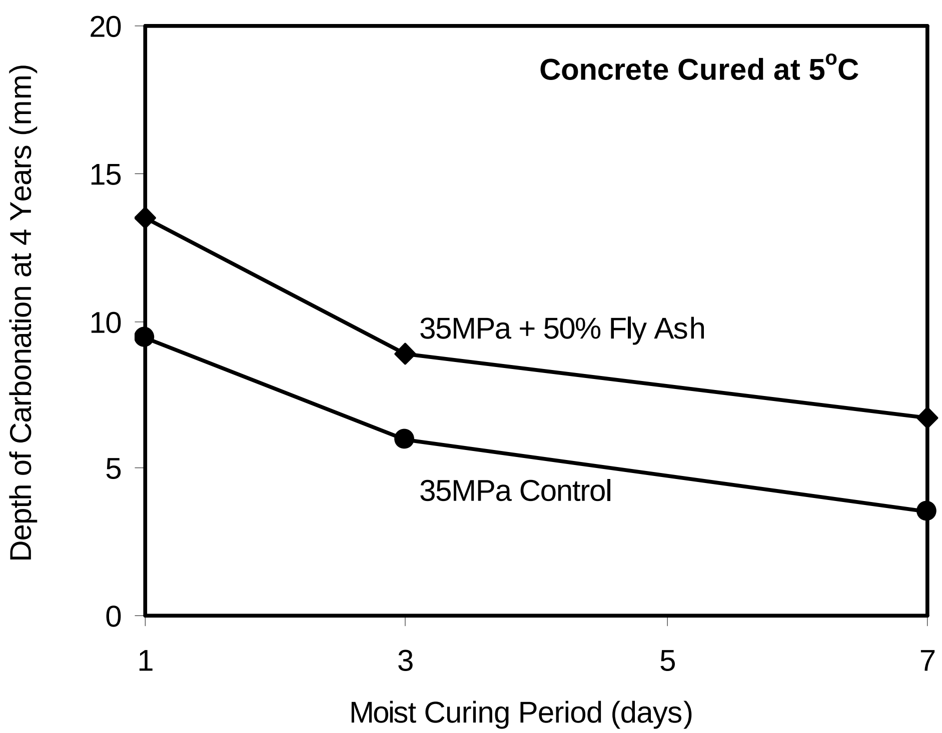

Fig. 6 Effect of Curing on Carbonation of Concrete Cured at 5°C

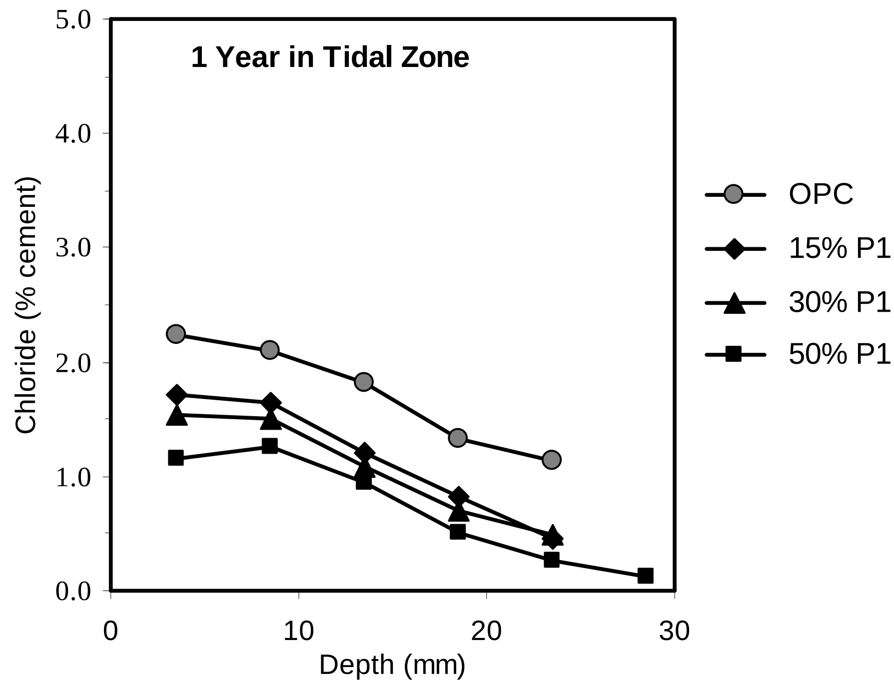

Fig. 7 Chloride Penetration in 35-MPa Concrete after 1 Year

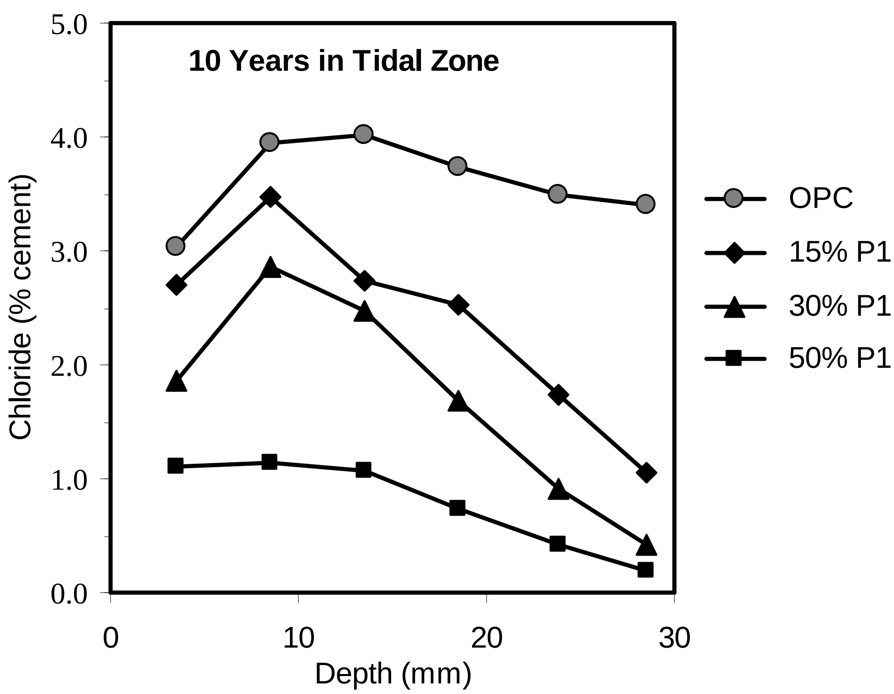

Fig. 8 Chloride Penetration in 35-MPa Concrete after 10 Years

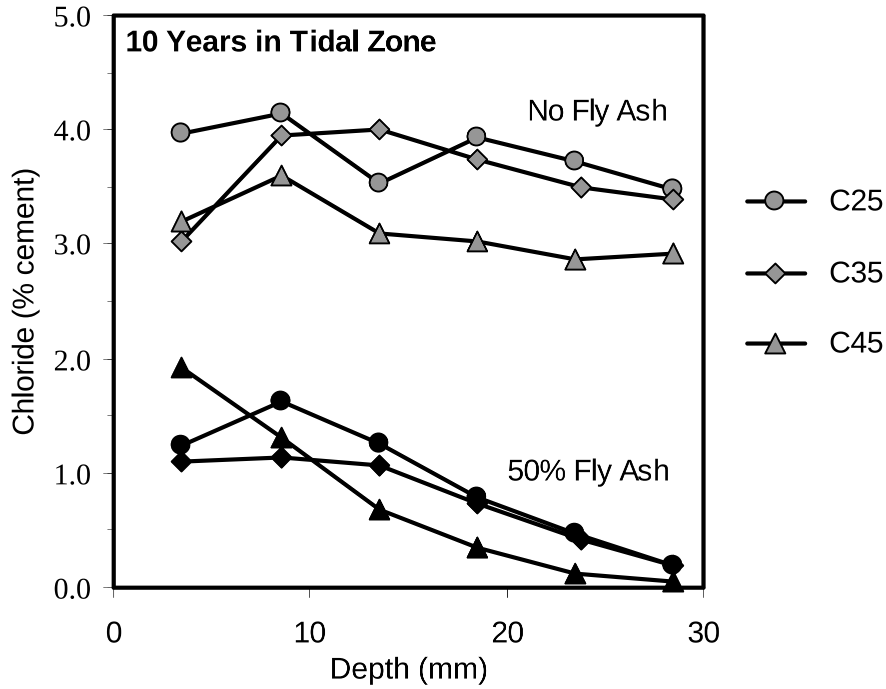

Fig. 9 Effect of Strength on Chloride Penetration after 10 Years

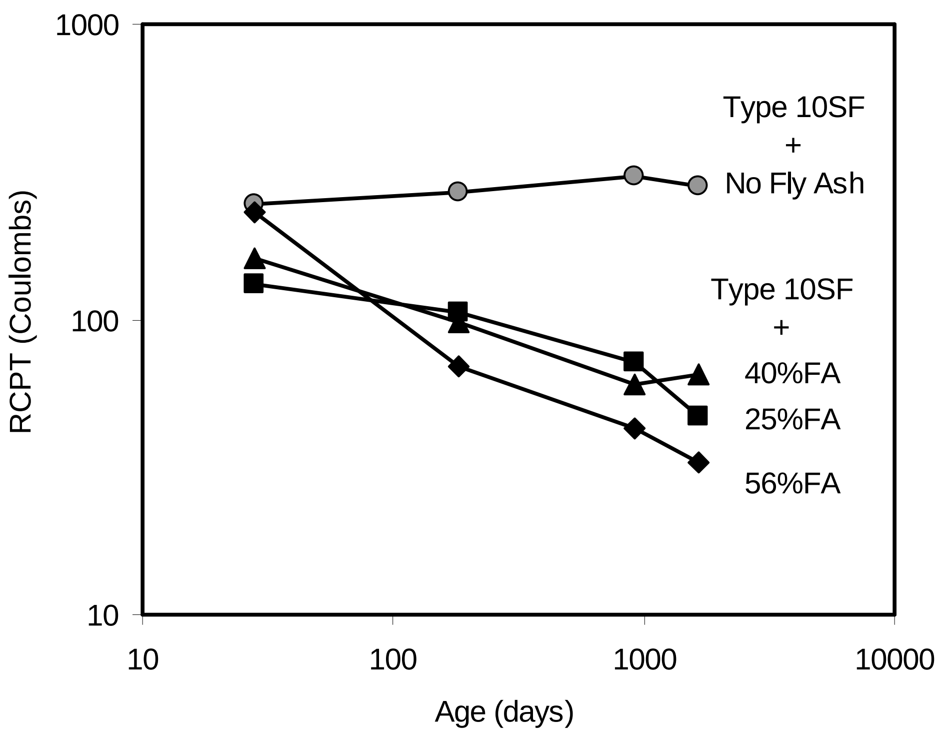

Fig. 10 Chloride Permeability of Concrete with Silica Fume Plus Fly Ash

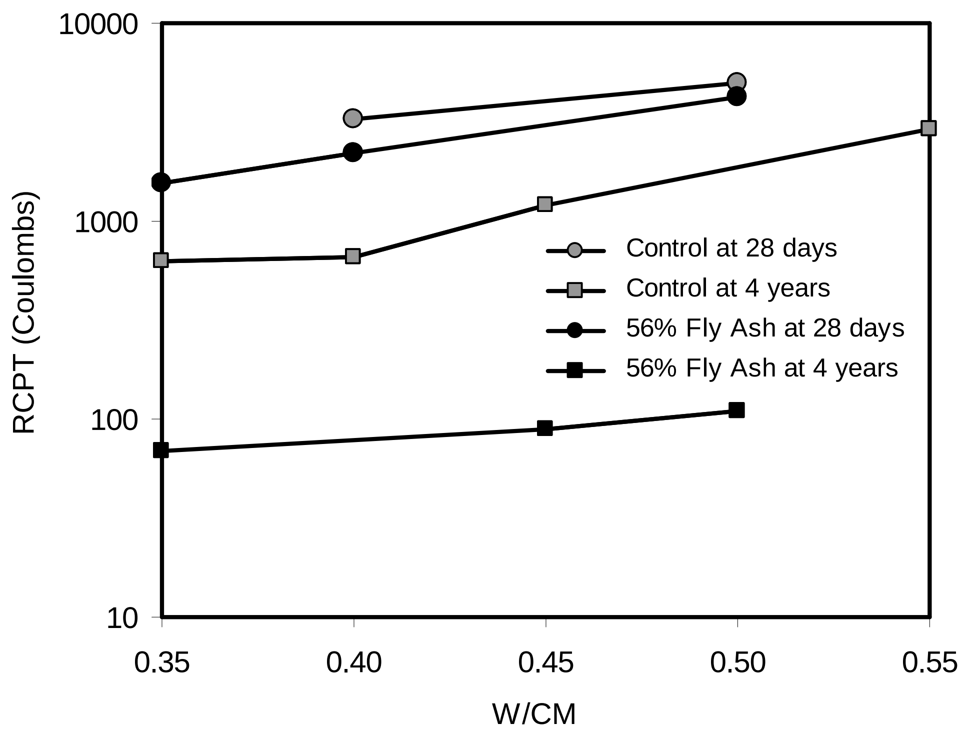

Fig. 11 Effect of W/CM and Fly Ash on "Chloride Permeability"

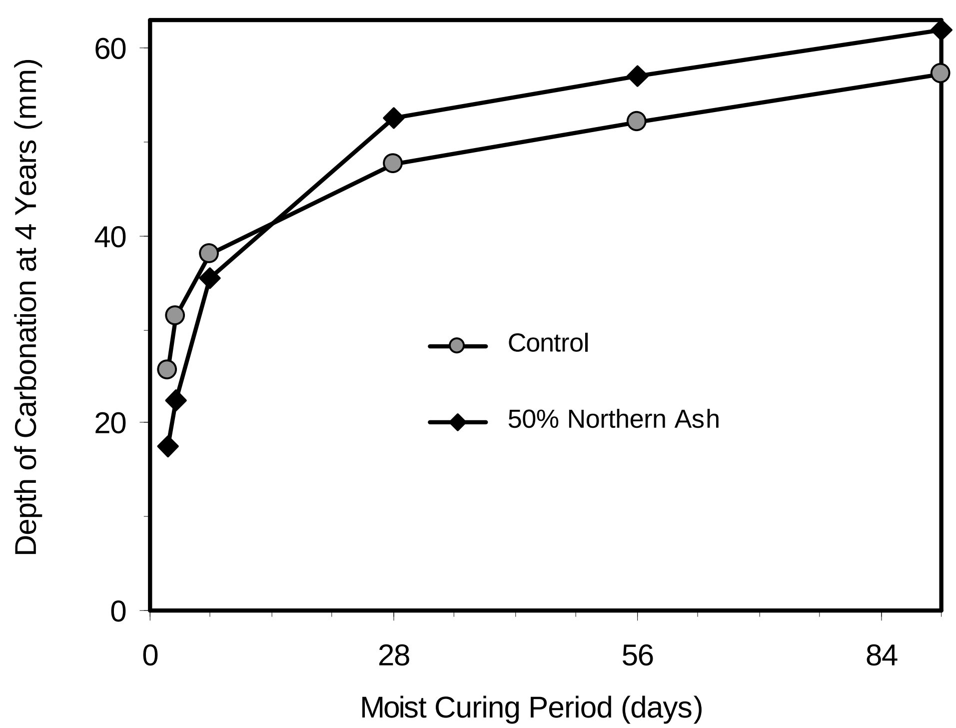

Fig. 12 Strength Development of High-Volume Fly Ash Concrete