

Optimizing the Use of Fly Ash in Concrete

Syed Burhan Qutub Andrabi

M. Tech, Civil Engineering

1. Introduction

Fly ash is used as a supplementary cementitious material (SCM) in the production of portland cement concrete. A supplementary cementitious material, when used in conjunction with portland cement, contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity, or both. As such, SCM's include both pozzolans and hydraulic materials. A pozzolan is defined as a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value, but that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties. Pozzolans that are commonly used in concrete include fly ash, silica fume and a variety of natural pozzolans such as calcined clay and shale, and volcanic ash. SCM's that are hydraulic in behavior include ground granulated blast furnace slag and fly ashes with **high calcium contents (such fly ashes display both pozzolanic and hydraulic behavior)**.

The potential for using fly ash as a supplementary cementitious material in concrete has been known almost since the start of the last century (Anon 1914), although it wasn't until the mid-1900s that significant utilization of fly ash in concrete began (for example, USBR 1948) following the pioneering research conducted at the University of California, Berkeley (Davis 1937). The last 50 years has seen the use of fly ash in concrete grow dramatically with close to 15 million tons used in concrete, concrete products and grouts in the U.S. in 2005 (ACAA 2006).

Historically, fly ash has been used in concrete at levels ranging from 15% to 25% by mass of the cementitious material component. The actual amount used varies widely depending on the application, the properties of the fly ash, specification limits, and the geographic location and climate. Higher levels (30% to 50%) have been used in massive structures (for example, foundations and dams) to control temperature rise. In recent decades, research has demonstrated that high dosage levels (40% to 60%) can be used in structural applications, producing concrete with good mechanical properties and durability (Marceau 2002).

Increasing the amount of fly ash in concrete is not without shortcomings. At high levels problems may be encountered

with extended set times and slow strength development, leading to low early-age strengths and delays in the rate of construction. These drawbacks become particularly pronounced in cold-weather concreting. Also, the durability of the concrete may be compromised with regards to resistance to deicer-salt scaling and carbonation.



Figure 1: Fly ash, a powder resembling cement, has been used in concrete since the 1930s. (IMG12190)

For any given situation there will be an optimum amount of fly ash that can be used in a concrete mixture which will maximize the technical, environmental, and economic benefits of fly ash use without significantly impacting the rate of construction or impairing the long-term performance of the finished product. The optimum amount of fly ash will be a function of wide range of parameters and must be determined on a case-by-case basis.

This report discusses issues related to using low to very high levels of fly ash in concrete and provides guidance for the use of fly ash without compromising the construction process or the quality of the finished product. For the purposes of this document the replacement levels shown in Table 1 will be used to represent low, moderate, high and very high levels of fly ash.

Table 1: Dosage Levels of Fly Ash

Level of Fly Ash	Classification
% by mass of total cementitious material	
<15	Low
15-30	Moderate
30-50	High
>50	Very High

Production of Fly Ash

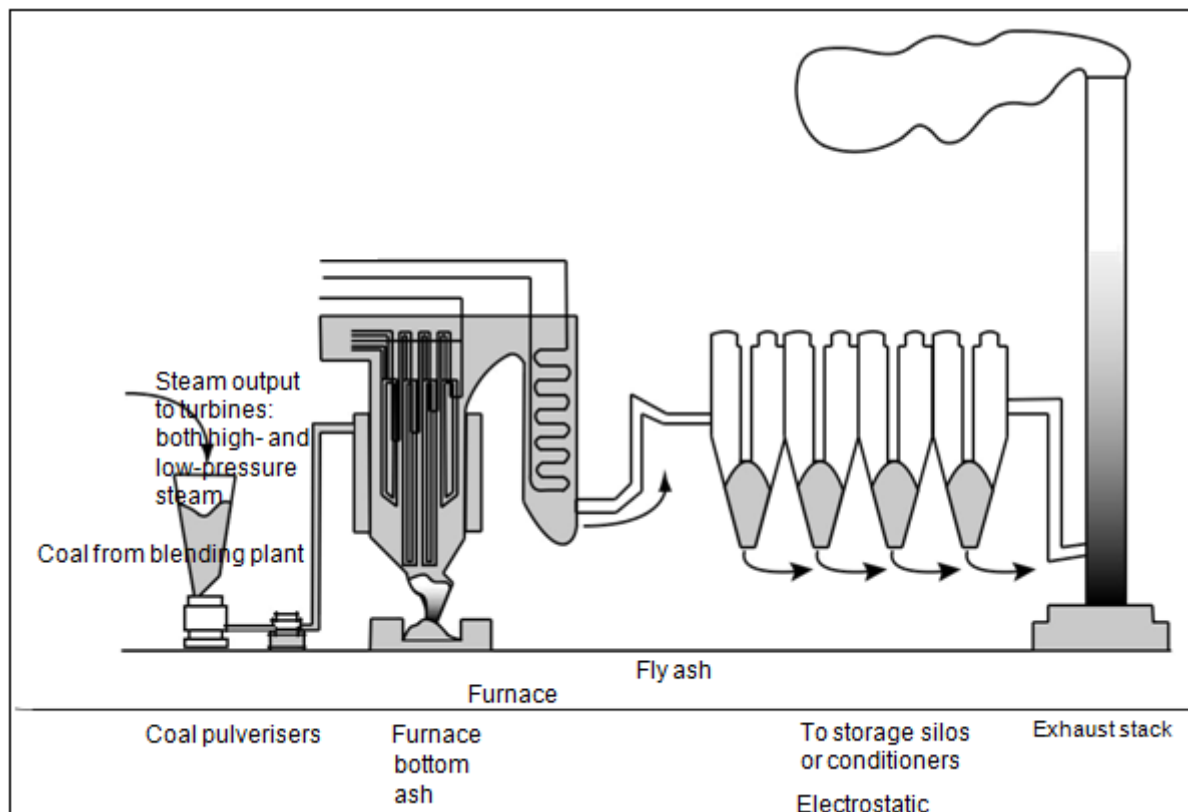


Figure 2. Schematic layout of a coal-fired electrical generating station (Khrew 2017)

In the production of fly ash, coal is first pulverized in grinding mills before being blown with air into the burning zone of the boiler. In this zone the coal combusts producing heat with temperatures reaching approximately 1500°C (2700°F). At this temperature the non-combustible inorganic minerals (such as quartz, calcite, gypsum, pyrite, feldspar and clay minerals) melt in the furnace and fuse together as tiny molten droplets. These droplets are carried from the combustion chamber of a furnace by exhaust or flue gases. Once free of the burning zone, the droplets cool to form spherical glassy particles called fly ash (Figure 3). The fly ash is collected from the exhaust gases by mechanical and electrostatic precipitators.

The Nature of Fly Ash

Fly ash is a by-product of burning pulverized coal in an electrical generating station. Specifically, it is the unburned residue that is carried away from the burning zone in the boiler by the flue gases and then collected by either mechanical or electrostatic separators (Figure 2). The heavier unburned material drops to the bottom of the furnace and is termed bottom ash; this material is not generally suitable for use as a cementitious material for concrete, but is used in the manufacture of concrete masonry block.

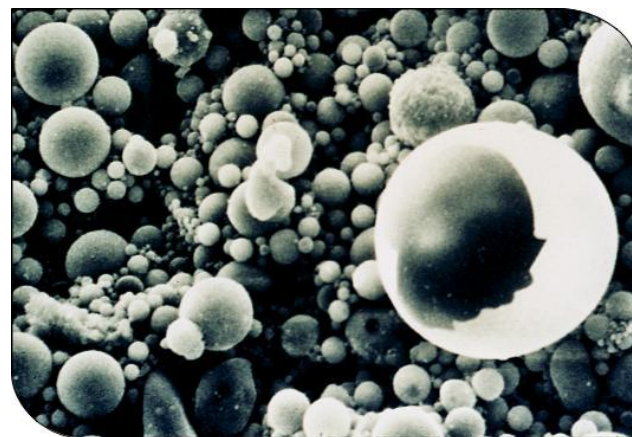


Figure 3: Micrograph showing spherical fly ash particles (IMG12309)

Fly ash is a pozzolanic material. It is a finely-divided amorphous aluminosilicate with varying amounts of calcium, which when mixed with portland cement and water, will react with the calcium hydroxide released by the hydration of portland cement to produce various calcium-silicate hydrates (C-S-H) and calcium-aluminate hydrates. Some fly ashes with higher amounts of calcium will also display cementitious behavior by reacting with water to produce hydrates in the absence of a source of calcium hydroxide. These pozzolanic reactions are beneficial to the concrete in that they increase the quantity of the cementitious binder phase (C-S-H) and, to a lesser extent, calcium-aluminate hydrates, improving the long-term strength and reducing the permeability of the system. Both of these mechanisms enhance the durability of the concrete. Detailed information on the nature of fly ash and pozzolanic reactions in concrete can be found in the ACI Committee

232 report on *Fly Ash in Concrete* and other sources (Helmuth 1987).

The performance of fly ash in concrete is strongly influenced by its physical, mineralogical and chemical properties. The mineralogical and chemical composition are dependent to a large extent on the composition of the coal and since a wide range of domestic and imported coals (anthracite, bituminous, sub-bituminous and lignite) are burned in different generating stations in North America, the properties of the fly ash can be very different between sources and collection methods. The burning conditions within a power plant can also affect the properties of the fly ash.

Table 2: ASTM Specification for Fly Ash

Class	Description in ASTM C 618	Chemical Requirements
F	Fly ash normally produced from burning anthracite or bituminous coal that meets the applicable requirements for this class as given herein. This class of fly ash has pozzolanic properties.	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \geq 70\%$
C	Fly ash normally produced from lignite or sub-bituminous coal that meets the applicable requirements for this class as given herein. This class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties. Note: Some Class C fly ashes may contain lime contents higher than 10%.	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \geq 50\%$

The most widely used specification for fly ash in India is ASTM C618 *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete* (AASHTO M 295). This specification divides fly ash into two classes based on its source of origin and composition as described in Table 2.

Many fly ashes produced from lignite or sub-bituminous coals meet the chemical requirement of Class F fly ash ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \geq 70\%$). Such fly ashes may be classed as Class F or Class C and are sometimes referred to as Class F/C or C/F fly ashes. In Canada, the specification covering fly ash is CSA A3001 *Cementitious Materials for Use in Concrete* which separates fly ash into three types based on the calcium content of the fly ash as shown in Table 3.

Table 3: CSA Specification for Fly Ash

Type F	< 8% CaO
Type CI	8 - 20% CaO
Type CH	> 20% CaO

The calcium content of the fly ash is perhaps the best indicator of how the fly ash will behave in concrete (Thomas 1999), although other compounds such as the alkalis (Na_2O and K_2O), carbon (usually measured as LOI), and sulfate (SO_3) can also affect the performance of the fly ash. Low-calcium fly ashes (< 8% CaO) are invariably produced from anthracite or bituminous coals and are predominantly composed of alumino-silicate glasses with varying amounts of crystalline quartz, mullite, hematite and magnetite. These crystalline phases are essentially inert in concrete and the glass requires a source of alkali or lime (for example, $\text{Ca}(\text{OH})_2$) to react and form cementitious hydrates. Such fly

ashes are pozzolanic and display no significant hydraulic behavior. High-calcium fly ashes (> 20% CaO) may be produced from lignite or sub-bituminous coals and are comprised of calcium-alumino-silicate glass and a wide variety of crystalline phases in addition to those found in low-calcium fly ash. Some of these crystalline phases will react with water and this, coupled with the more reactive nature of the calcium-bearing glass, makes these fly ashes react more rapidly than low-calcium fly ashes and renders the fly ash both pozzolanic and hydraulic in nature. These fly ashes will react and harden when mixed with water due to the formation of cementitious hydration products. If the calcium content of the fly ash is high enough, it is possible to make concrete with moderate strength using the fly ash as the sole cementing material (Cross 2005).

In addition to providing an indication of the mineralogy and reactivity of the fly ash, the calcium content is also useful in predicting how effective the fly ash will be in terms of reducing the heat of hydration (Thomas 1995), controlling expansion due to alkali-silica reaction (Shehata 2000), and providing resistance to sulfate attack (Shashiprakash 2002). These issues are addressed in sections **Effect of Fly Ash on the Properties of Fresh Concrete** and **Durability**.

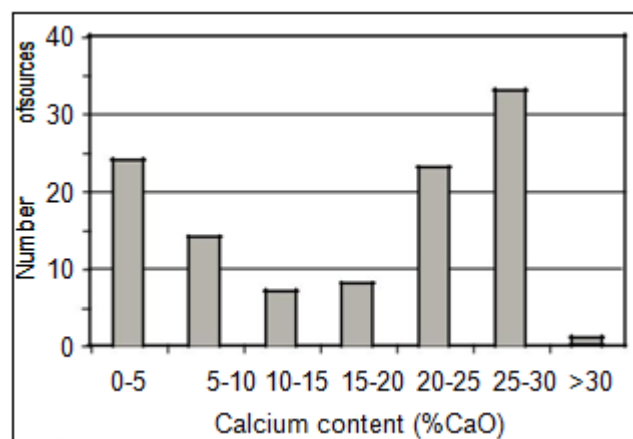


Figure 4: Distribution of fly ashes by calcium content

Figure 4 shows the distribution in terms of calcium content of fly ashes from 110

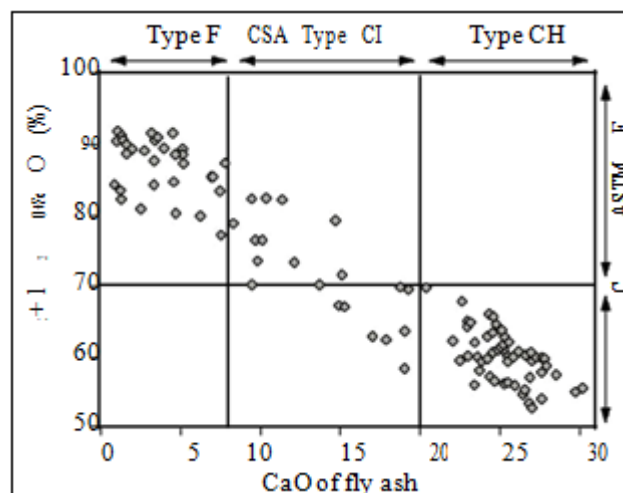


Figure 5: Relationship between calcium oxide content and the sum of the oxides ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$)

Figure 5 compares the calcium content with the sum of the oxides ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) for the same fly ashes. All fly ashes that meet CSA Type F or Type CH would be classified as Class F and Class C by ASTM C618. However, most fly ashes that meet CSA Type CI could be classified by ASTM as either Class C based on the coal source or as Class F based on the sum of the oxides.

The quantity of alkalis in fly ash can range from less than 1% Na_2Oeq^1 up to 10% Na_2Oeq . The average alkali content of the 110 fly ashes from commercial sources in North America is 2.4% with 85% of these fly ashes having alkali contents below 3% Na_2Oeq . There are a few sources that produce fly ashes with much higher alkali levels (for example, 5 to 10% Na_2Oeq). These fly ashes tend to be very reactive as the alkalis raise the pH of the pore solution when they are mixed in concrete and the high pH accelerates the dissolution of the glass in the fly ash. Particular attention should be paid to the (alkali-silica) reactivity of the aggregates when high-alkali fly ashes are used in concrete. There is no limit placed on the alkali content of fly ash by either ASTM C618 or CSA A3001.

The sulfate content of fly ash generally ranges from less than 0.1% to 5% SO_3 (average = 1.5% SO_3 for 110 fly ash analyses discussed above). In exceptional cases the sulfate content may exceed 5% SO_3 and in some sources the sulfate content has exceeded 7% SO_3 . ASTM C618 limits the sulfate content of fly ash to 5% SO_3 when the material is to be used in concrete. CSA A3001 imposes the same limit but allows the limit to be exceeded provided it is demonstrated by testing that the fly ash does not produce deleterious expansion.

The only other limit placed on the composition of the fly ash by ASTM and CSA specifications is a maximum allowable loss-on-ignition (LOI). The LOI limit in ASTM C618 is 6% for Class F and Class C fly ash, ¹Equivalent alkali: $\text{Na}_2\text{Oeq} = \text{Na}_2\text{O} + 0.658 \times \text{K}_2\text{O}$. However, the specification allows Class F fly ashes with up to 12% LOI to be approved by the user if either acceptable performance records or laboratory test results are made available. The LOI limit for CSA A3001 is 8% for Type F fly ash and 6% for Types CI and CH fly ashes.

Excessive amounts of magnesia (MgO) or free lime (CaO) in cementitious materials may cause unsoundness (undesirable volume change) when these materials are used in concrete. Both ASTM C618 and CSA A3001 require fly ash to pass an autoclave expansion test (ASTM C151) to demonstrate soundness.

Fly ash may also be introduced to concrete through the use of a blended hydraulic cement consisting of portland cement, fly ash and possibly other cementitious components. Blended cements are specified by ASTM C595, *Standard Specification for Blended Hydraulic Cements*, ASTM C1157, *Standard Performance Specification for Hydraulic Cement* and CSA A3001 *Cementitious Materials for Use in Concrete*. A Portland Cement Association survey (PCA 2000) showed that out of the 29.5 million cubic meters (38.6 million cubic yards) of ready-mixed concrete produced by the survey respondents in the year 1998, 15.8 million m^3

(20.7 million yd^3) contained fly ash (54% of production) and only 94,000 m^3 (123,000 yd^3) of that amount contained blended cement (0.3% of production). The use of blended cements containing fly ash (or other SCMs) is much more common in Europe; however, their use is growing in North America. In 2005, one percent of cement produced in the United States was blended cement containing fly ash (PCA 2007).

2. Effect of Fly Ash on the Properties of Fresh Concrete

Workability

The use of good quality fly ash with a high fineness and low carbon content reduces the water demand of concrete and, consequently, the use of fly ash should permit the concrete to be produced at a lower water content when compared to a portland cement concrete of the same workability (Figures 6 and 7). Although the exact amount of water reduction varies widely with the nature of the fly ash and other parameters of the mix, a gross approximation is that each 10% of fly ash should allow a water reduction of at least 3%.

A well-proportioned fly ash concrete mixture will have improved workability when compared with a portland cement concrete of the same slump. This means that, at a given slump, fly ash concrete flows and consolidates better than a conventional portland cement concrete when vibrated. The use of fly ash also improves the cohesiveness and reduces segregation of concrete. The spherical particle shape lubricates the mix rendering it easier to pump and reducing wear on equipment (Best 1980) (Figure 3).

It should be emphasized that these benefits will only be realized in well-proportioned concrete. The fresh properties of concrete are strongly influenced by the mixture proportions including the type and amount of cementing material, the water content, the grading of the aggregate, the presence of entrained air, and the use of chemical admixtures.

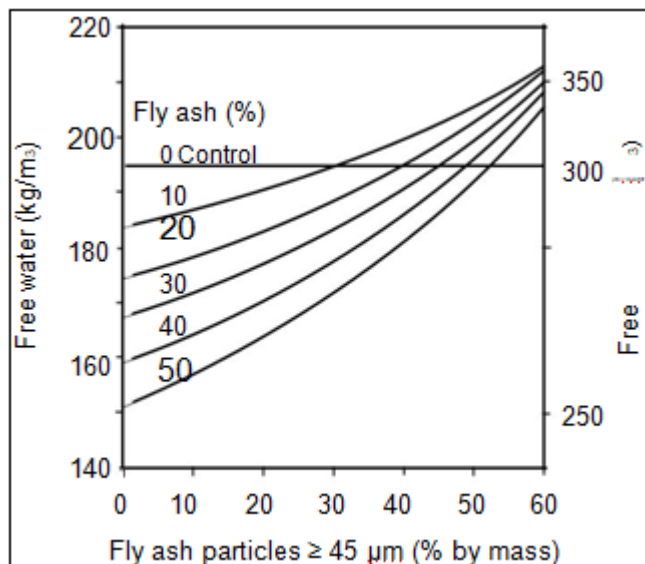


Figure 6: Effect of fly ash fineness on water demand of concretes proportioned for equal slump (Owens 1979).

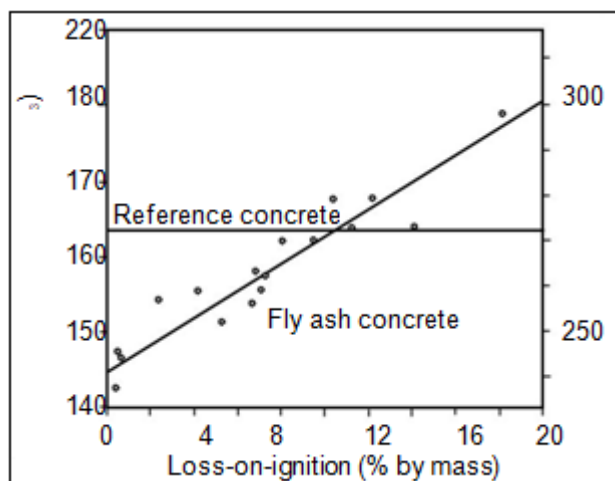


Figure 7: Effect of fly ash LOI on water demand of concretes proportioned for equal slump (adapted from Sturup 1983)

The improved rheological properties of high-volume fly ash (HVFA) concrete make it suitable for use in self-consolidating concrete (SCC) (Bouzoubaa 2001 and Nehdi 2004). Coarser fly ashes or those with high levels of carbon generally produce a smaller reduction in water demand and some may even increase water demand (Figures 6 and 7). Careful consideration should be given before using these fly ashes in concrete especially at higher levels of replacement in structural concrete.

Bleeding

Generally fly ash will reduce the rate and amount of bleeding primarily due to the reduced water demand (Gebler 1986). Particular care is required to determine when the bleeding process has finished before any final finishing of exposed slabs.

High levels of fly ash used in concrete with low water contents can virtually eliminate bleeding. Therefore, the freshly placed concrete should be finished as quickly as possible and immediately protected to prevent plastic

shrinkage cracking when the ambient conditions are such that rapid evaporation of surface moisture is likely.

The guidance given in ACI 305, *Hot Weather Concreting* should be followed. An exception to this condition is when fly ash is used without an appropriate water reduction, in which case bleeding (and segregation) will increase in comparison to portland cement concrete.

Air Entrainment

Concrete containing low-calcium (Class F) fly ashes generally requires a higher dose of air-entraining admixture to achieve a satisfactory air-void system. This is mainly due to the presence of unburned carbon (Figure 8) which absorbs the admixture. Consequently, higher doses of air-entraining admixture are required as either the fly ash content of the concrete increases or the carbon content of the fly ash increases. The carbon content of fly ash is usually measured indirectly by determining its loss-on-ignition (LOI).

The increased demand for air entraining admixture should not present a significant problem to the concrete producer provided the carbon content of the fly ash does not vary significantly between deliveries. It has been shown that as the admixture dose required for a specific air content increases, the rate of air loss also increases (Gebler 1983).

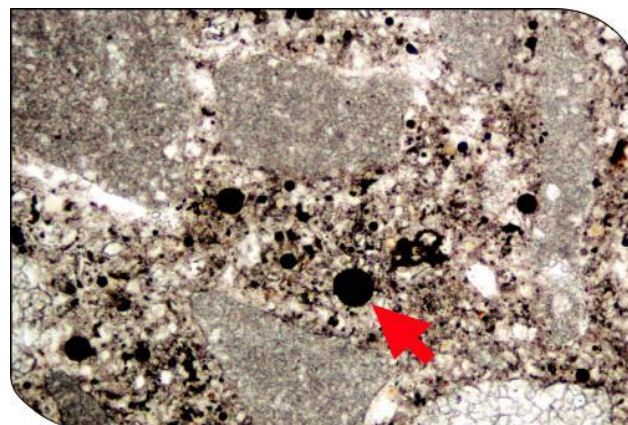


Figure 8: Concrete in thin-section. Fly ashes with a high content of unburnt carbon (highlighted with arrow) generally require higher doses of air-entraining admixture

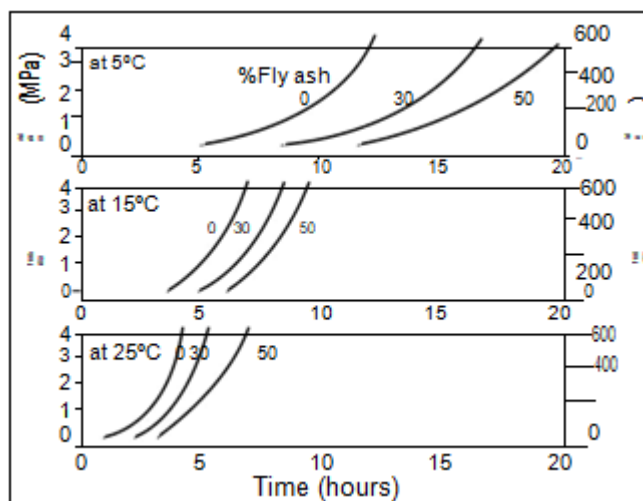


Figure 9: Effect of fly ash and temperature on the penetration resistance of setting concretes proportioned for

equal strength at 28 days and workability (Concrete Society 1991).

Generally, high-calcium fly ashes require a smaller increase in the air-entrainment dose compared to low-calcium fly ashes. Some Class C fly ashes high in water-soluble alkali may even require less admixture than those mixes without fly ash (Pistilli 1983).

Setting Time

The impact of fly ash on the setting behavior of concrete is dependent not only on the composition and quantity of fly ash used, but also on the type and amount of cement, the water-to-cementitious materials ratio (w/cm), the type and amount of chemical admixtures, and the concrete temperature. It is fairly well-established that low-calcium fly ashes extend both the initial and final set of concrete as shown in Figure 9.

During hot weather the amount of retardation due to fly ash tends to be small and is likely to be a benefit in many cases.

During cold weather, the use of fly ash, especially at high levels of replacement, can lead to very significant delays in both the initial and final set. These delays may result in placement difficulties especially with regards to the timing of finishing operations for floor slabs and pavements or the provision of protection to prevent freezing of the plastic concrete. Practical considerations may require that the fly ash content is limited during cold-weather concreting. The use of set-accelerating admixtures may wholly or partially offset the retarding effect of the fly ash. The setting time can also be reduced by using an ASTM C150 Type III (or ASTM C1157 Type HE) cement or by increasing the initial temperature of the concrete during production (for example, by heating mix water and/or aggregates).

Higher-calcium fly ashes generally retard setting to a lesser degree than low-calcium fly ashes, probably because the hydraulic reactivity of fly ash increases with increasing calcium content. However, the effect of high-calcium fly ashes is more difficult to predict because the use of some of these ashes with certain cement-admixture combinations can lead to either rapid (or even flash) setting or to severely retarded setting (Wang 2006 and Roberts 2007).

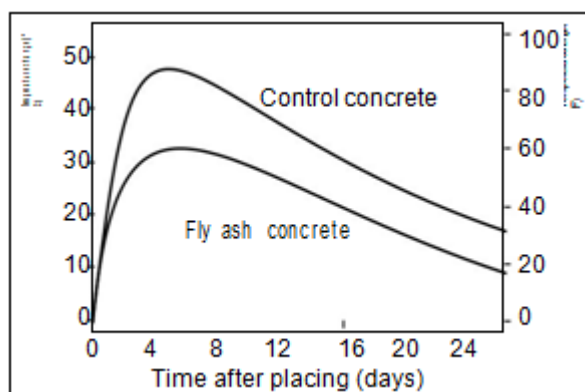


Figure 10: Effect of fly ash on temperature rise in concrete dams (Mustard 1959).

With all fly ashes, but especially with higher-calcium fly ashes, testing is required before a new fly ash source is introduced to a plant. Testing can determine the effect of the fly ash on the setting behavior of concrete produced with the other plant materials. This testing should be conducted at a range of fly ash levels and at different temperatures.

Heat of Hydration

The reduction in the rate of the heat produced and hence the internal temperature rise of the concrete has long been an incentive for using fly ash in mass concrete construction. One of the first full-scale field trials was conducted by Ontario Hydro (Mustard 1959) during the construction of the Otto Holden Dam in Northern Ontario around 1950. Two elements of the dam, measuring 3.7 x 4.3 x 11.0 m (12 x 14 x 36 ft), were constructed with embedded temperature monitors. One element was constructed using a concrete with 305 kg/m³ (514 lb/yd³) of portland cement and the other with a concrete with the same cementitious material content but with 30% of the portland cement replaced with a Class F fly ash. Figure 10 shows the results from this study indicating that the use of fly ash reduced the maximum temperature rise over ambient from 47°C to 32°C (85°F to 58°F).

In massive concrete pours where the rate of heat loss is small, the maximum temperature rise in fly ash concrete will primarily be a function of the amount and composition of the portland cement and fly ash used, together with the temperature of the concrete at the time of placing. Concrete with low portland cement contents and high fly ash contents are particularly suitable for minimizing autogenous temperature rises. For example, Langley and coworkers (Langley 1992) cast three 3.05 x 3.05 x 3.05 m (10 x 10 x 10 ft) blocks with embedded thermocouples, and showed that the incorporation of 55% fly ash reduced the peak temperature by 29°C (52°F) when the cementitious material content was held constant and by 53°C (95°F) when the total cementitious content was reduced (Table 4). The high-volume fly ash (HVFA) concrete mixes (with ~ 55% Class F fly ash) were effective in reducing both the rate of heat development and the maximum temperature reached within the concrete block.

Table 5 shows data from a later study (Bisaillon 1994) using large monoliths (2.5 x 4.0 x 5.0 m (8.2 x 13.1 x 16.4 ft)) cast with HVFA concrete with Type F fly ash.

These results again indicate that the autogenous temperature rise can be kept very low with high-volume fly ash when the total cementitious content is kept low (in this case 280 kg/m³ (472 lb/yd³)). This property can be very advantageous when early-age strength is not important. Higher early-age strengths can be achieved by raising the cementitious material content of the HVFA system, although this does result in an increase in the autogenous temperature rise.

HVFA concrete systems have been successfully used in commercial applications to control the temperature rise in large placements (Mehta 2000, Mehta 2002, and Manmohan 2002).

Most published work on the effects of fly ash on the rate of heat development and temperature rise in concrete have focused on low-calcium Class F fly ashes. Work by the Bureau of Reclamation (Dunstan 1984) indicated that the rate of heat development generally increases with the calcium content of the ash. Fly ashes high in calcium may produce little or no decrease in the heat of hydration (compared to plain portland cement) when used at normal replacement levels. Similar results have been reported for studies

Table 4: Temperature Rise in Large Concrete Blocks Produced with HVFA Concrete

Mix	Cement kg/m ³ (lb/yd ³)	Fly ash kg/m ³ (lb/yd ³)	w/cm	Max. temp °C (°F)	Time to max. (h)
1	400 (674)	-	0.33	83 (181)	24
2	180 (303)	220 (370)	0.27	54 (129)	96
3	100 (168)	125 (211)	0.49	30 (86)	168

(Langley 1992)

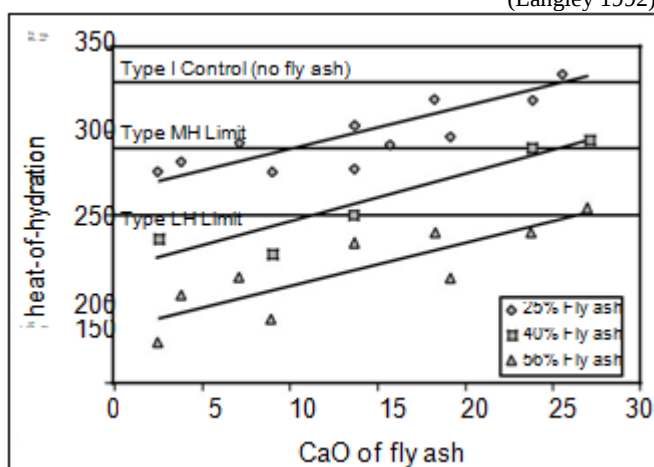


Figure 11: Effect of fly ash on heat of hydration using conduction (isothermal) calorimetry

on insulated mortar specimens (Barrow 1989), where the use of high-calcium ash (> 30% CaO) was found to retard the initial rate of heat evolution but did not reduce the maximum temperature rise. However, Carrette (1993) reported that there was no consistent trend between ash composition and temperature rise for concretes containing high levels of fly ash (56% by mass of cementitious material). Calcium levels of the ashes used in the study ranged up to 20% CaO. Conduction calorimetry studies conducted at Ontario Hydro in Canada (Thomas 1995) using a wide range of fly ashes (2.6% to 27.1% CaO) showed that the 7-day heat of hydration of cement-fly ash pastes was strongly correlated with the calcium content of the fly ash in agreement with Dunstan (1984). However, these studies also indicated that high-calcium fly ashes could be used to meet performance criteria for ASTM C150 Type IV or ASTM C1157 Type LH cements when used at a sufficient replacement level (Figure 11).

High levels of high-calcium (Class C) fly ash have been used to control the temperature rise in mass concrete foundations. One example is the concrete raft foundation for the Windsor Courthouse (Ellis Don 1996). This 10,000 m³ (13,000 yd³) concrete raft was 1.2 m (4 ft) thick and was placed in pours 1400 m³ to 1700 m³ (1830 yd³ to 2220 yd³)

in volume, with placement rates (pumping the concrete) of up to 100 m³/h (130 yd³/h). Concrete with 50% Class C fly ash was used to control temperature while thermocouples were used to determine when thermal blankets could be removed without causing thermal shock.

Table 5: Temperature Rise in Large Concrete Monoliths Produced with HVFA Concrete

Mix	Cement kg/m ³ (lb/yd ³)	Fly ash kg/m ³ (lb/yd ³)	w/cm	Strength MPa (psi)		Max. Temp °C (°F)	Time to max. (h)
				1-day	3-day		
1	365 (600) Type I	-	0.45	10.3 (1495)		68 (154)	29
2	125 (211) Type I	155 (261)	0.46	1.6 (230)	5.1 (740)	44 (111)	53
3	170 (287) Type I	220 (370)	0.29	8.4 (1220)	15.6 (2260)	54 (129)	57
4	330 (556) Type II	-	0.5	7.3 (1060)	14 (2030)	55 (131)	75
5	125 (211) Type I	155 (261)	0.41	2.5 (365)	8.4 (1220)	47 (117)	98

(Bisaillon 1994)

Finishing and Curing

The use of fly ash can lead to significant retardation of the setting time, which means that finishing operations may have to be delayed. At normal temperatures, the rate of the pozzolanic reaction is slower than the rate of cement hydration, and fly ash concrete needs to be properly cured if the full benefits of its incorporation are to be realized. When high levels of fly ash are used it is generally recommended that the concrete is moist cured for a minimum period of 7 days. It has been recommended that the duration of curing be extended further (for example, to 14 days) where possible, or that a curing membrane be placed after 7 days of moist curing (Malhotra 2005). If adequate curing cannot be provided in practice, the amount of fly ash used in the concrete should be limited.

The finishing and curing requirements for high-volume fly ash concrete exposed to cyclic freezing and thawing in the presence of de-icing salts is discussed in the section **Effect of Fly Ash on the Durability of Concrete**.

3. Effect of Fly Ash on the Properties of Hardened Concrete

Compressive Strength Development

Figure 12 shows the text book effect on compressive strength of replacing a certain mass of portland cement with an equal mass of low-calcium (Class F) fly ash and maintaining a constant w/cm. As the level of replacement increases the early-age strength decreases. However, long-term strength development is improved when fly ash is used and at some age the strength of the fly ash concrete will

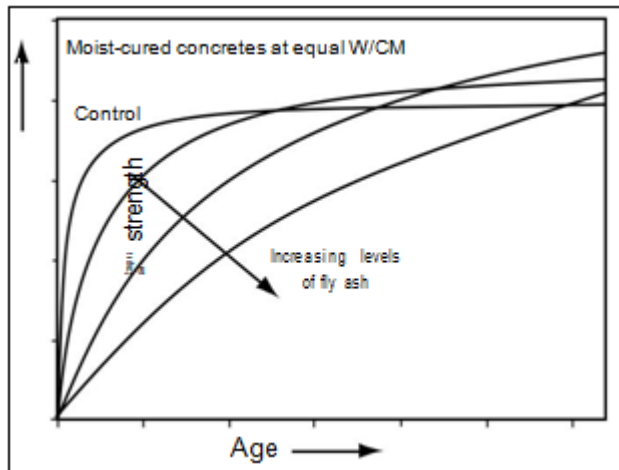


Figure 12: Text book effect of fly ash on compressive strength development of concrete.

equal that of the portland cement concrete so long as sufficient curing is provided. The age at which strength parity with the control (portland cement) concrete is achieved is greater at higher levels of fly ash. The ultimate strength achieved by the concrete increases with increasing fly ash content, at least with replacement levels up to 50%. Generally, the differences in the early-age strength of portland cement and fly ash concrete are less for fly ash with higher levels of calcium, but this is not always the case.

In many cases, concrete is proportioned to achieve a certain minimum strength at a specified age (typically 28 days). This can be achieved by selecting the appropriate water-to-cementitious materials ratio (w/cm) for the blend of cement and fly ash being used. The w/cm required will vary depending on the level of fly ash replacement, the composition of the ash, and the age and strength specified. If the specified strength is required at 28 days or earlier this will usually require lower values of w/cm when using higher levels of fly ash. A lower w/cm can be achieved by a combination of (i) reducing the water content by either taking advantage of the lower demand in the presence of fly ash, or by using a water-reducing admixture, or both; and (ii) increasing the total cementitious content of the mix. When the strength is required at early ages (for example, 1 day) the use of an accelerating admixture may be considered.

The rate of early-age strength development is strongly influenced by temperature, and this is especially the case for fly ash concrete as the pozzolanic reaction is more sensitive to temperature than is the hydration of portland cement. Figure 13 shows the effect of using temperature-matched curing for concrete with and without 30% fly ash (Bamforth 1980) proportioned to equal 28-day strength. Temperature-matched curing increased the strength of fly ash concrete at all ages up to 28 days, the effect being most pronounced at early ages: at 3 days the strength of the temperature-matched cured cubes was almost double that of cubes stored under standard conditions. Temperature-matched curing resulted in a small increase in the strength of portland cement concrete at 3 days (5% increase over standard-cured concrete), but significantly impaired the strength at later ages. In large sections, or in concrete placed at high temperatures, the difference in the early-

age insitu strength of concretes with and without fly ash may be much lower than that predicted on the basis of test specimens stored under standard laboratory conditions. It follows that in small sections placed in cold weather, the strength gain of fly ash concrete could be lower than that predicted on the basis of cylinders stored under standard conditions. Given the high sensitivity of fly ash concrete to curing temperature, especially when higher levels of fly ash are used, it may be prudent to consider the use of methods (such as temperature-matched curing or cast-in-place cylinders) to determine the in-situ strength of the concrete.

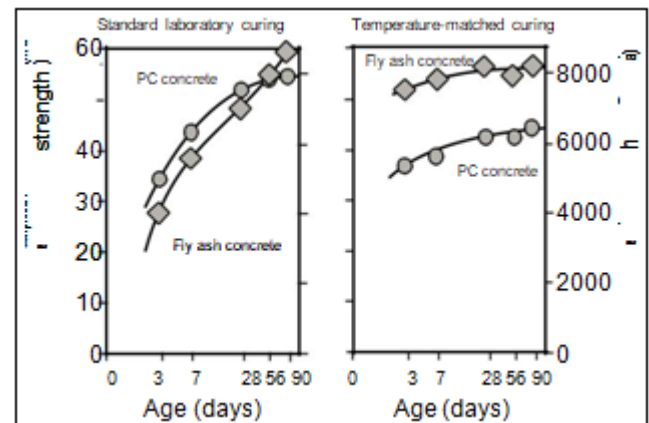


Figure 13: Strength development of 100 mm (4 in.) concrete cubes subjected to standard laboratory and temperature-matched curing (Bamforth 1980)

If relatively high strengths are required at very early ages, it will usually be necessary to limit the amount of fly ash used unless appropriate means are taken to accelerate the early strength contribution of the fly ash (for example, use of heat-curing or accelerators, or both), especially when the concrete is placed at low temperatures.

Other Mechanical Properties

The relationships between the tensile strength, flexural strength and elastic modulus, and the compressive strength of concrete are not significantly affected by the presence of fly ash at low and moderate levels of replacement. Malhotra and Mehta (2005) indicate that the long-term flexural and tensile strength of HVFA concrete may be much improved due to the continuing pozzolanic reaction strengthening the bond between paste and the aggregate. They further suggest that the elastic modulus of HVFA concrete may be increased due to the presence of significant amounts of unreacted fly ash particles which act as fine aggregate and because of the very low porosity of the interfacial zone (Malhotra 2005).

Creep

The creep of concrete is influenced by a large number of parameters and the effect of fly ash on creep will depend to some extent on how the effect is measured. For example, if loaded at an early age, fly ash concrete may exhibit higher amounts of creep than portland cement concrete because it has a lower compressive strength (Lane 1982 and Yuan 1983). However, if concretes are loaded at an age when they have attained the same strength, fly ash concrete will exhibit less creep because of its continued strength gain (Lane 1982 and Ghosh 1981).

The creep of HVFA concrete tends to be lower than portland cement concrete of the same strength and this has been attributed to the presence of unreacted fly ash (Sivasundaram 1991). It is also likely that the very low water and paste contents attainable in HVFA concrete (and concurrently high aggregate content) play an important role in reducing the creep of concrete with high levels of fly ash.

Drying Shrinkage

For concrete with dimensionally-stable aggregates the key parameters affecting drying shrinkage are; the amount of water in the mix, the w/cm, and the fractional volume of aggregate.

In well-cured and properly-proportioned fly ash concrete, where a reduction in the mixing water content is made to take advantage of the reduced water demand resulting from the use of the fly ash, the amount of shrinkage should be equal to or less than an equivalent portland cement concrete mix.

It has been reported that the drying shrinkage of high volume fly ash concrete is generally less than conventional concrete (Malhotra 2005 and Atis 2003) and this is undoubtedly due to the low amounts of water used in producing such concrete.

4. Effect of Fly Ash on the Durability of Concrete

Abrasion Resistance

It has been demonstrated that the abrasion resistance of properly finished and cured concrete is primarily a function of the properties of the aggregate and the strength of concrete regardless of the presence of fly ash (Gebler 1986). This appears to hold true at higher levels of fly ash (Malhotra 2005, Atis 2002, and Siddique 2004).

Permeability and Resistance to the Penetration of Chlorides

Fly ash reduces the permeability of concrete to water and gas provided the concrete is adequately cured (Thomas 2002). This has been attributed to a refinement in the pore structure (Thomas 1989 and Marsh 1985).

It is now more common to use indirect measures of concrete permeability such as ASTM C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, (often referred to as the Rapid Chloride Permeability Test, or RCPT) due to difficulties in measuring the water permeability of concrete with low w/cm and supplementary cementing materials such as fly ash. Despite the known limitations of this test (it measures electrical conductivity, not permeability) it does provide a reasonable indication of the ability of concrete to resist chloride penetration (Stanish 2001) and there have been hundreds of publications reporting how various parameters (materials, mixture proportions, curing, maturity, etc.) affect the outcome of this test.

Figure 14 shows RCPT data from the author for concretes (w/cm = 0.40) with various levels of CSA Type CI fly ash (~13% CaO) continuously moist cured for up to approximately

7 years. At 28 days, the charge passed increases with fly ash content, with the chloride permeability of the concrete containing 56% fly ash being almost double that of the control concrete without fly ash. However, there is a rapid decrease in the charge passed with time for fly ash concretes, and by 180 days there is a reversal in the trend with chloride permeability decreasing with increasing fly ash content. After, approximately 7 years the concretes with 25%, 40% and 56% fly ash are 4 times, 14 times, and 29 times less electrically conductive than the control concrete, respectively.

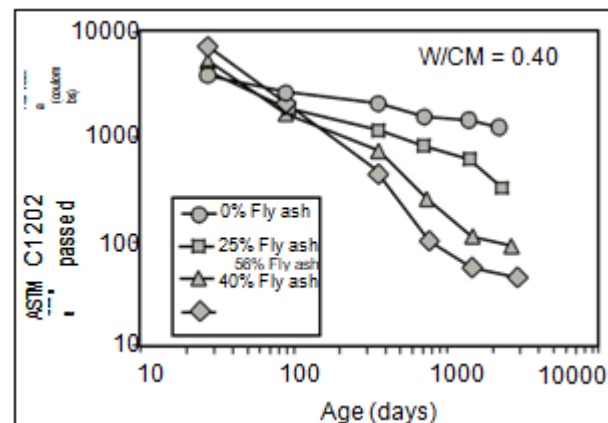


Figure 14: Effect of fly ash content and age on the chloride permeability of concrete

Malhotra (2000) reported RCPT data for concrete cores extracted from large blocks that had been stored outdoors protected from direct precipitation for 10 years. Six concrete mixes, including a HVFA concrete mix, were used and the test results are shown in Table 6.

After 10 years, five of the concrete mixes are considered to have a very low chloride penetrability according to the ASTM C1202 criteria (charge passed between 100 and 1000 coulombs), yet no measurable charge was passed through the HVFA concrete specimen during the six-hour test period.

Naik (2003) reported RCPT data for concrete cores extracted from HVFA concrete pavements at the age of 7 to 14 years with the results shown in Table 7. The chloride permeability decreased with increasing fly ash contents and, for a given level of replacement, was lower for concrete with Class F fly ash compared to Class C fly ash.

Table 6: RCPT Data for Cores Taken from 10-Year-Old Concrete Blocks

Mix	SCMs	Cementitious content kg/m ³ (lb/yd ³)	w/cm	RCPT at 10 years (coulombs)
1	7% silica fume+28% slag	485 (817)	0.29	100
2	35% slag	484 (816)	0.28	235
3	8% silica fume	488 (823)	0.27	565
4	12% silica fume	486 (819)	0.27	120
5	57% fly ash	350 (590)	0.29	0
6	100% Portland cement	485 (817)	0.27	380

(Malhotra 2000)

All the results indicate that the concretes have very low to negligible chloride penetrability based on the ASTM C1202 criteria.

These data from mature HVFA concrete structures would seem to indicate that the concrete becomes nearly impermeable to chlorides. However, as mentioned previously, the RCPT measures electrical conductivity as opposed to permeability. In saturated concretes, the conductivity will be a function of both the pore structure and the composition of the pore solution. Supplementary cementing materials are known to reduce the concentration of ions in the pore solution and, hence, the electrical conductivity of the solution. Thus, reductions in the RCPT cannot be solely ascribed to beneficial changes in the pore structure and concomitant reductions in permeability. However, the reductions in RCPT observed with HVFA concrete are impressive and certainly indicate substantial increases in the resistance of the material to chloride ion penetration. Steady-state diffusion tests conducted on cement pastes indicate that fly ash (and other SCMs) reduces the chloride diffusion coefficient, the magnitude of the reduction in short-term laboratory tests with 20% to 30% fly ash being anywhere from 2.5 times (Page 1982) to 10 times (Ngala 2000). Testing of concrete exposed to marine environments show that the beneficial effects of fly ash become more significant with time as the concrete containing fly ash shows substantial reductions in chloride penetrability with time (Bamforth 1999, Thomas 1999, and Thomas 2004). Figure 15 shows chloride concentration profiles at different ages for concrete exposed in a marine tidal zone for up to 10 years (Thomas 2004). The concretes were proportioned to provide the same strength

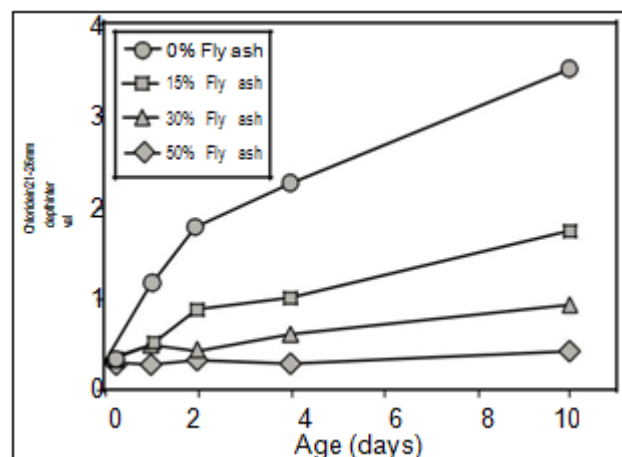


Figure 16: Effect of fly ash content on chloride penetration.

at 28 days and contain zero and 50% fly ash. The concretes were unsaturated at the time of first exposure and there is a fairly rapid penetration of chlorides into both concretes. However, beyond this time there are clearly substantial differences between the two concretes in terms of the resistance to chloride ion penetration. The concrete without fly ash offered little resistance, whereas there was very little increase in the chloride content of the fly ash concrete with time, especially at depth. Figure 16 shows the chloride content in the depth interval from 21 to 26 mm (0.82 to 1.02 inches) beneath the surface for concretes with different amounts of fly ash exposed for various periods of time. The chloride penetrated to this depth rapidly in the control concrete without fly ash. The rate of chloride penetration decreased significantly with fly ash content and the chloride content at this depth barely increased at all beyond the initial 28-day period for the concrete with 50% fly ash.

Table 7: RCPT Data for Cores Taken from Concrete Pavements

Mix	Mix	Cementitious content kg/m ³ (lb/yd ³)	w/cm	Age (years)	RCPT (coulombs)
A-1	70% Class C	335 (565)	N/A	14	113
B-5	50% Class C	350 (590)	0.26	8	217
C-4	19% Class C	350 (590)	0.29	8	566
D-2	67% Class F	400 (674)	0.31	7	65
E-3	53% Class F	389 (656)	0.31	7	77
F-6	35% Class F	416 (701)	0.31	8	155

(Naik, 2003)

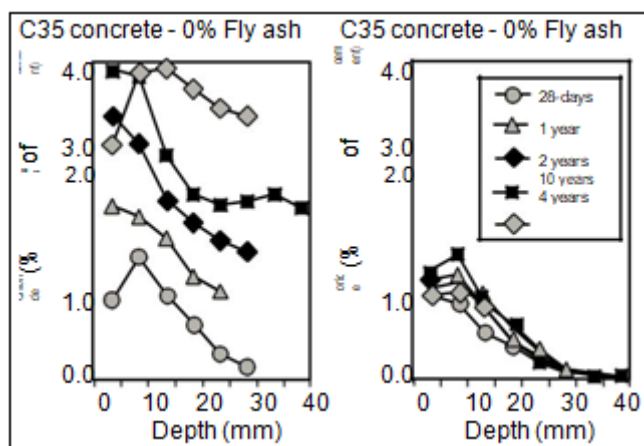


Figure 15: Chloride profiles into marine-exposed concrete at 10 years

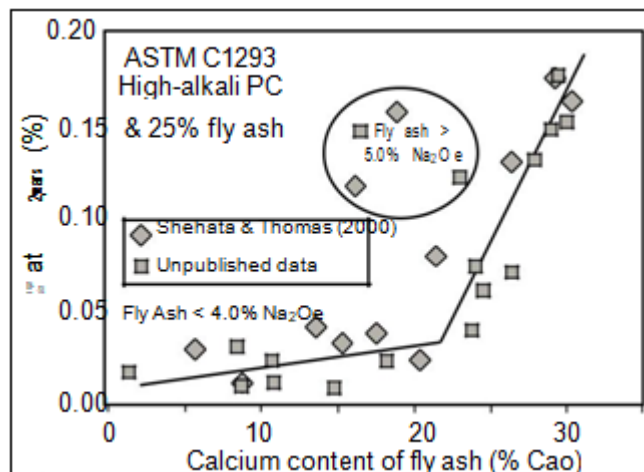


Figure 17: Effect of fly ash composition on expansion of concrete (reactive siliceous limestone coarse aggregate and 25% fly ash).

Alkali-Silica Reaction

It is well established that low-calcium (Class F) fly ash is capable of controlling damaging alkali-silica reaction (ASR) in concrete at moderate levels of replacement (20% to 30%) and the effect has been ascribed to the reduced concentration of alkali hydroxides in the pore solution when fly ash is present. High-calcium Class C fly ashes are less effective in this role (Shehata 2000 and Shehata 1999).

Figure 17 shows the expansion of concrete prisms containing high-alkali cement (raised to 1.25% Na_2Oeq), a reactive siliceous limestone coarse aggregate and different fly ashes (all used at a replacement level of 25%) after 2-years storage over water at 38°C (100°F). The expansion is plotted against the calcium oxide content of the fly ash. The data show that most fly ashes with low to moderate calcium oxide and alkali contents (< 20% CaO and < 4% Na_2Oeq) are effective in controlling damaging expansion (for instance, expansion $\leq 0.040\%$ at 2 years) when used at a 25% level of replacement with this aggregate. High-alkali/high-calcium Class C fly ashes (> 20% CaO) are less effective and the expansion at 2 years generally increases with the calcium oxide content of the fly ash. However, the data in Figure 18 show that Class C fly ashes can be used provided that they are used at higher levels of replacement. Some fly ashes may have to be used at replacement levels above 50%.

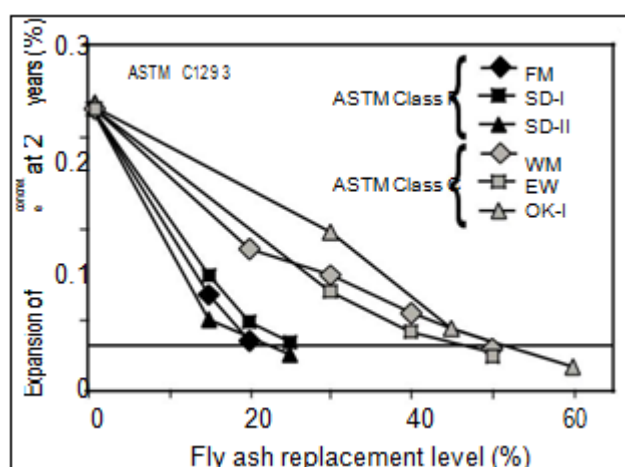


Figure 18: Effect of fly ash composition and level of replacement on expansion of concrete (reactive siliceous limestone coarse aggregate)

Generally, the level of fly ash required to suppress deleterious expansion of concrete increases with the following:

- Increased calcium and alkali content of fly ash;
- Decreased silica content of fly ash;
- Increased aggregate reactivity;
- Increased alkali availability from portland cement (and other components of the concrete); and
- Increased alkali in the environment (for example, from de-icing or anti-icing salts).

There is a low risk of ASR expansion occurring in the field when very high-volume fly ash concrete with 50% or more fly ash is used, however, testing is recommended when high-calcium fly ash is used. High-alkali fly ashes (> 5% Na_2Oeq) are not recommended for use with potentially reactive aggregates.

Sulfate Resistance

A number of studies (Dunstan 1980, Mehta 1986, von Fay 1989, and Tikalsky 1992) have demonstrated that the use of sufficient quantities of low-calcium Class F fly ash can increase the resistance of concrete to chemical attack when the concrete is exposed to sulfate-bearing soils or groundwater. However, these studies have also shown that

high-calcium Class C fly ashes are generally not effective in this role and may even increase the rate and extent of sulfate attack. Shashiprakash and Thomas (2001) showed that blends of high- C_3A Type I portland cement and high-calcium fly ashes (> 20% CaO) could not meet the requirements for moderate sulfate resistance (for instance, mortar bar expansion

< 0.10% at 6 months when tested in ASTM C1012) even when the level of fly ash was increased to 40% by mass of the total cementitious material.

Studies on concrete exposed to wetting and drying cycles at the sulfate soils facility of the California Department of Transportation showed that the principle mechanism of deterioration in this environment is physical sulfate attack due to the formation and crystallization of sodium sulfate¹ (Stark 2002). Under these conditions, fly ash did not lead to any significant improvement in performance even when up to 40% of a Class F fly ash was used.

Carbonation

The rate of carbonation of properly-proportioned and well-cured concrete is slow. Provided adequate cover is given to embedded steel reinforcement, carbonation-induced corrosion of the steel is unlikely to occur during the typical service life of a reinforced concrete structure. However, problems with steel corrosion initiated by carbonation are occasionally encountered in concrete structures due to a combination of either poor-quality concrete, inadequate curing, or insufficient cover.

It has been documented that concrete containing fly ash will carbonate at a similar rate compared with portland cement concrete of the same 28-day strength (Tsukayama 1980, Lewandowski 1983, Matthews 1984, Nagataki 1986, Hobbs 1988, and Dhir 1989).

This means that fly ash increases the carbonation rate provided that the basis for comparison is an equal w/cm. It has also been shown that the increase due to fly ash is more pronounced at higher levels of replacement and in poorly-cured concrete of low strength (Thomas 1992 and Thomas 2000). Even when concretes are compared on the basis of equal strength, concrete with fly ash (especially at high levels of replacement) may carbonate more rapidly in poorly-cured, low strength concrete (Ho 1983, Ho 1997, Thomas 1992, and Thomas 2000).

Based on 10-year carbonation data collected at the Building Research Establishment (BRE) in the U.K., Thomas (2004) established carbonation-rate coefficients² for concrete with a range of strengths, fly ash levels and moist-curing periods, and stored outdoors with protection from direct precipitation³. The values of these carbonation rates are presented in Table 8.

These data show that, within a single strength grade, concretes containing fly ash carbonate at a faster rate (especially for lower-strength concrete with higher levels of fly ash) after only 1 day moist curing. To achieve similar performance as concrete without fly ash, concrete containing 50% fly ash must be moist-cured for an

extended period of time or else be designed have a higher strength.

A recent study reported carbonation data for HVFA concrete (Bouzoubaa 2006). In this study the maximum carbonation coefficient for concrete with 56% fly ash and $w/cm = 0.32$ when moist cured for 7 days was $5.04 \text{ mm/y}^{1/2}$ for indoor exposure and $2.51 \text{ mm/y}^{1/2}$ for unprotected outdoor exposure. This compares with $1.14 \text{ mm/y}^{1/2}$ and $0 \text{ mm/y}^{1/2}$ (for instance, no measurable carbonation at 7 years) for portland cement concrete with the same w/cm . This indicates that the use of high levels of fly ash resulted in much increased carbonation rates. However, it was concluded by this study that carbonation is not an issue for well-cured HVFA concrete based on the calculated time-to-corrosion (> 200 years) for reinforcing steel with a depth of cover of 40 mm (1.5 in)¹ in concrete exposed outdoors.

¹Presumably the cyclic dehydration-hydration of sodium sulfate (i.e. thernadite-mirabalite transformation) also contributed to this form of attack.

²Rate coefficient k is calculated from carbonation data assuming that the depth of carbonation, d , is related to time, t , through the relationship $d = k t^{1/2}$ (where d is measured in mm , t in years, and k in $\text{mm/y}^{1/2}$)

³This environment is considered to be the most conducive for carbonation-induced corrosion of steel reinforcement. Drier environments (for example, normal laboratory conditions) may lead to increased carbonation rates, but there is insufficient moisture available to sustain the corrosion process. Concrete stored outdoors and exposed to frequent precipitation will carbonate at a very slow rate. However, if the concrete is protected from direct precipitation, the conditions can favor both carbonation and corrosion. The undersides of balconies, ledges and beams are exposed to this type of condition and it is in these locations that problems due to carbonation-induced corrosion are sometimes found.

Table 8: Effect of Strength, Curing and Fly Ash on Carbonation Rate Coefficient, k ($\text{mm/y}^{1/2}$)

Strength grade* MPa (psi)	Moist curing (days)	Fly ash content (%)			
		0	15	30	50
18 (2610)	1	6.8	8.3	8.3	10
	3	5.8	6.3	6.2	8.4
	7	4.9	4.6	5.3	7.1
25 (3625)	1	4.9	4.9	5.2	6.4
	3	3.1	3.7	3.9	5.9
	7	2.4	3.3	3.2	4.8
32 (4640)	1	2.4	2.8	3	3.9
	3	0.71	2.1	2.1	2.6
	7	0.28	1.3	1.2	1.9

*Strength grade based on characteristic 28-day cylinder strengths (converted from original cube strengths).

The conclusion of Bouzoubaa (2006) is only valid if the following conditions are met: (i) HVFA concrete is proportioned with a very low w/cm (≤ 0.32), (ii) concrete is moist-cured for at least 7 days, (iii) concrete is directly exposed to moisture during service (for instance, not protected from precipitation), and (iv) the specified minimum cover requirements (for example, 40 mm (1.5 in)) are met. If there are changes in the mixture proportions, if the concrete is not directly exposed to moisture (for

example, it is protected from rainfall), and if 7-days curing and 40-mm cover are specified, but not achieved

in practice, the time-to-corrosion will be reduced substantially. For example, the data in Table 8 show that 25 MPa (3625 psi) concrete with 50% fly ash ($W/CM = 0.41$ for this mix) has a carbonation coefficient of $k = 5.85 \text{ mm/y}^{1/2}$ if it is only moist-cured for 3 days. If the cover actually achieved in practice is only 30 mm (1.2 in), corrosion of the steel will be initiated in just 26 years.

In summary, when high-volume fly ash concrete is used in areas prone to carbonation (for example, sheltered outdoor exposure), particular attention must be paid to ensuring that the concrete mix proportions, period of moist curing, and depth of cover are adequate for the purpose.

¹ Minimum cover in Canadian specifications (CSA A23.1) for concrete exposed outdoors provided there are no chlorides present and the concrete is not cast against and permanently exposed to earth. Note that ACI 318 requires a minimum cover for concrete not exposed to weather or in contact with ground as follows:

slabs, walls, joists: No. 14 and No. 18 bars- 40 mm (1.5 in); No. 11 bar and smaller- 20 mm ($3/4 \text{ in}$);

beams, columns: primary reinforcement, ties, stirrups, spirals- 40 mm (1.5 in);

shells, folded plate members: No. 6 bar and larger- 20 mm ($3/4 \text{ in}$); No. 5 bar, W31 or D31 wire, and smaller- 12.5 mm ($1/2 \text{ in}$).

Resistance to Cyclic Freezing and Thawing, and Deicer Salt Scaling

Concrete can be resistant to cyclic freezing and thawing provided it has sufficient strength and an adequate air-void system, and the aggregates are frost-resistant. This holds true for fly ash concrete regardless of the fly ash content. However, a number of laboratory studies have shown that concrete containing fly ash may be less resistant to scaling when subjected to freezing and thawing in the presence of deicer salts (Timms 1956, Gebler 1986, Johnston 1987, Johnston 1994, Whiting 1989, and Afrani 1994) and the lower scaling resistance of fly ash concrete is more pronounced in lean concretes (low cementitious material content) or concretes with high levels of cement replaced with fly ash. However, some studies which have shown satisfactory performance at levels of fly ash up to 30% (Gebler 1986, Gifford 1987, and Bilodeau 1991) and, in some cases, even higher (Naik 1995). Based on a review of published data from laboratory tests and a survey of fly ash concrete structures exposed to de-icing salts the following observation have been made (Thomas 1997):

- Scaling increases as the w/cm increases;
- Scaling mass loss generally increases with fly ash content, especially at high levels of replacement (for instance ≥ 40 to 50%);
- Results from concrete containing fly ash tend to be more variable; and
- The use of curing compounds (membranes) reduces scaling; this is particularly noticeable for fly ash concrete.

The results from laboratory scaling tests (ASTM C672) do not correlate well with field performance. Fly ash concrete has performed well in a number of demonstration projects where samples cast from the same concrete mixtures during construction and tested in the laboratory have performed poorly.

Fly ash concrete is likely to provide satisfactory scaling performance (for example, mass loss $< 0.8 \text{ kg/m}^2$ and visual rating ≤ 2 to 3) provided the water-cementitious material, w/cm, does not exceed 0.45 and the level of fly ash does not exceed 20 to 30%. This, of course, assumes an adequate air-void system is present in the concrete and that proper construction practices are adhered to.

High-volume fly ash concrete invariably performs poorly in laboratory scaling tests even when the w/cm is maintained at very low values. Testing (Bilodeau 1998) using various curing regimes, including different curing compounds, showed severe scaling (mass loss $> 4 \text{ kg/m}^2$ and visual ratings = 5) for concrete with high levels of fly ash (58%) and low w/cm ($= 0.32$) regardless of curing, although the use of curing compounds did improve the performance to some degree. The field performance of HVFA concrete with regards to deicer salt scaling is varied. HVFA concrete demonstration projects in Halifax included trial sections of two sidewalks, one placed in 1990 and the other in 1994 (Langley 1998). The first placement had a cementitious content of 390 kg/m^3 (657 lb/yd^3) and contained 55% of low-calcium Class F fly ash, and in 1998 it was reported (Langley 1998) to have

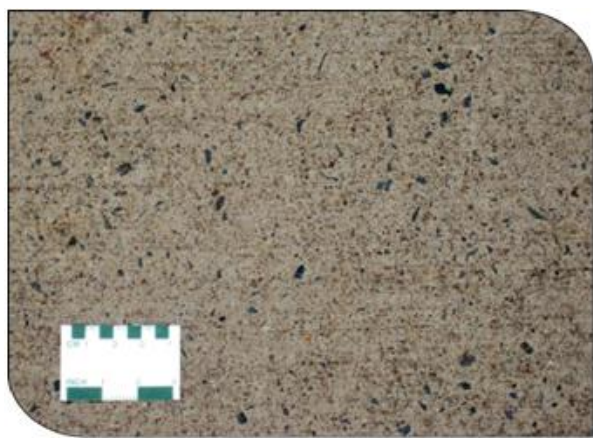


Figure 19: Sidewalks in UNIVERSITY - portland cement concrete mix

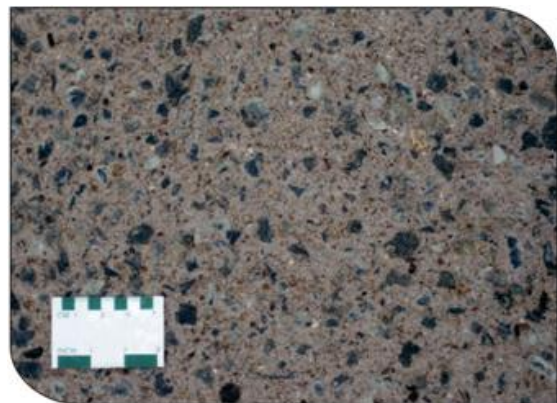


Figure 20: Sidewalks in UNIVERSITY - HFVA concrete mix.

shown excellent performance that was at least equivalent to the surrounding concrete. The second placement had a cement content of 400 kg/m^3 (674 lb/yd^3), a fly ash content of 55% (Class F) and water content of 110 kg/m^3 (185 lb/yd^3), resulting in w/cm = 0.275. Figures 19 and 20 show the visual appearance of the control and HVFA concrete mix in the summer of 2006, after 12 winters. The HVFA concrete has scaled heavily (significantly more so than the control) but is still serviceable. It should be noted that this concrete receives frequent applications of deicer salt and is exposed to more than 100 cycles of freeze-thaw per year (Malhotra 2005).

High-volume fly ash concretes used for the construction of trial pavement sections in Wisconsin were reported to have performed well with regards to scaling resistance after more than 10 years (Naik 2003). The six concrete mixtures used contained between 35 to 67% Class F fly ash and 19 to 70% Class C fly ash and w/cm in the range 0.26 to 0.31 (information on the water content of the concrete with 70% Class C fly ash is not available). The pavements were constructed between 1984 and 1991, and the concrete was placed by a slip-form paving machine. It has been reported (Naik 2003) that the HVFA concretes with up to 67% fly ash have shown only minor surface scaling and that the other sections (with up to 70% Class C fly ash) have shown very little damage due to scaling.

Although concrete containing moderate to high volumes of fly ash can be produced to be resistant to freeze-thaw action in the presence of deicer salts, it is apparent that its scaling resistance is more sensitive to mixture proportioning, method of placement, finishing and curing than portland cement concrete. When such levels of fly ash are used to produce concrete flatwork that will be exposed to deicer salts considerable attention should be paid to the quality of the concrete and placement practices.

Optimizing Fly Ash Content in Concrete

The properties of fresh concrete and the mechanical properties and durability of hardened concrete are strongly influenced by the incorporation of the fly ash into the mixture. The extent to which fly ash affects these properties is dependent not only on the level and the composition of the fly ash, but also on other parameters including the composition and proportions of the other ingredients in the concrete mixture, the type and size of the concrete component, the exposure conditions during and after placement, and construction practices. **Clearly there is no one replacement level best suited for all applications.**

For example, a concrete sidewalk placed in late fall, a few weeks before the first anticipated snowfall and deicer salt application, will require a different level of fly ash than a massive concrete foundation placed in the middle of summer. In some cases, it may prudent to limit the fly ash used to minimize its impact and, in other cases, it may be beneficial to maximize the amount of fly ash used. In other words, the fly ash content of a mixture needs to be optimized for each application.

Table 9 provides a summary of how fly ash, when used at moderate to high levels of replacement (15 to 50%), affects

the properties of concrete. The use of fly ash has both beneficial and detrimental effects. Thus, optimization involves reaching a compromise where the fly ash content selected is sufficient to achieve the required benefit without producing any significant harm. For example, if concrete is being produced with a potentially (alkali-silica) reactive aggregate in cold-weather construction, the concrete should contain enough fly ash to control ASR expansion, but not so much such that the setting and early strength gain is impacted, or the resistance to deicer salt scaling is reduced. Most times the process of optimization will involve changing other parameters of the mixture. In the example of the reactive aggregate and cold-weather concreting, a set accelerator could be used to compensate for the negative impact of fly ash on the setting and early strength gain, or a small amount of silica fume could be used to both offset the amount of fly ash needed to control ASR and to improve the early-age strength.

In massive concrete structures where the primary consideration is reducing heat and the risk of thermal cracking, the optimum replacement level is likely to be in the range of 40% to 60% fly ash (or even higher levels) unless there are some early-age-strength requirements. For ele-

ments such as footings, walls, columns and beams that do not require finishing the level of fly ash will likely be dictated by early-age-strength requirements. If there are no such requirements, a fly ash content of 40% to 60% may also be suitable provided that adequate curing is ensured. If 7 days moist curing cannot be provided, lower levels of fly ash should be used. For concrete flatwork, the amount of fly ash will depend not only on strength requirements (for example, for suspended slabs) but also the nature and timing of finishing operations. Obla (2003) suggests that fly ash contents of 40% to 50% are suitable for slabs that merely require a broom finish, but that the level of replacement may have to be reduced for slabs that require trowel finishing (for example, 25% to 50%) to avoid unwanted delays in finishing. The timing of joint cutting may also impact the level of fly ash that can be used in slabs. Another limitation for flatwork is the possibility of exposure to deicer salts and freeze-thaw cycles. For concrete exposed to these conditions it is prudent to limit the level of fly ash. Finally, when using higher dosage levels in reinforced concrete, consideration should be given to whether the combination of the concrete quality (w/cm), degree of moist curing, depth of cover, and exposure condition pose a risk of carbonation-induced corrosion.

Table 9: Effect of Fly Ash on the Properties of Concrete

Property	Effect of Fly Ash*	Guidance
Fresh concrete	Workability is improved and water demand is reduced for most fly ashes. Concrete is more cohesive and segregates less improved pumpability. Bleeding is reduced especially at high replacement levels.	Reduce water content by approximately 3% for each 10% fly ash compared to similar mix without fly ash. Take precautions to protect concrete when placing conditions accelerate the rate of moisture loss (see ACI 305, Hot Weather Concreting). Ensure bleeding has stopped before commencing final finishing operations
Set time	Extended—especially in cold weather. Certain combinations of fly ash, cement and chemical admixtures may cause rapid or severely retarded set at certain temperatures.	Consider reducing level of fly ash during cold weather. Test fly ash-cement-admixture compatibility.
Heat of hydration	Reduced for Class F fly ash at normal levels of replacement. Class C fly ashes have to be used at higher levels of replacement to reduce heat (for example $\geq 50\%$). Reduction increased by using high levels of replacement, low total cementitious contents, and low concrete placing temperatures.	Use Class F fly ash if temperature control is critical. Otherwise, use high levels of Class C fly ash and/or take other measures to reduce temperature, such as: reduce cement content, use low-heat (Type IV or LH) or moderate-heat (Type II or MH) cement, or lower concrete placing temperature (use crushed ice or liquid-nitrogen cooling).
Early-age strength	Reduced - especially at 1 day. Reduction is greater for Class F fly ashes and for higher replacement levels. Impact less for in-situ strength if there is significant autogenous temperature rise (for example, in large pours)	Consider reducing fly ash content if early-age strength is critical. Use accelerating admixtures, high-early strength cement (Type III or HE), or silica fume to compensate for reduced early-age strength.
Long-term strength	Increased. Effect increases with the level of fly ash.	Consider extending testing out to 56 days for mix design acceptance.
Permeability and chloride resistance	Reduced significantly - especially at later ages.	Adequate curing is essential if these benefits are to be achieved in the concrete close to the surface (cover concrete)
Expansion due to alkali-silica reaction	Reduced. Deleterious expansion can be completely suppressed by sufficient levels of replacement. For Class F fly ash (with up to 20% CaO) a replacement level of 20 to 30% fly ash is sufficient for most aggregates. Higher levels of Class C fly ash are required ($\geq 40\%$).	If a reactive aggregate is being used, Class F fly ash should be used, if available. If Class F fly ash is not available, consider using combinations of Class C fly ash with silica fume or slag. The level of fly ash required for a particular aggregate should be determined using appropriate testing (for instance, ASTM C1293 or ASTM C1567).
Sulfate resistance	Increased by Class F fly ashes. A dosage level of 20 to 30% Class F fly ash will generally provide equivalent performance to a Type II or V portland cement (ASTM C150) cement or a Type MS or HS hydraulic cement (ASTM C1157). Resistance to cyclic immersion in sodium sulfate solution and drying has been shown to be relatively unaffected by up to 40% fly ash.	Do not use Class C fly ash. Test cement—fly ash combinations using ASTM C1012. Consider using Class F fly ash with sulfate-resisting portland cement.
Resistance to carbonation	Decreased for all fly ashes. Significant decreases when high levels of fly ash are used in poorly-cured, low-strength (high w/cm) concrete.	Provide adequate curing for concrete containing fly ash. Ensure cover requirements are met.

Resistance to deicer-salt scaling	Decreased. Significant scaling occurs in laboratory tests on concrete with high levels of fly ash. Field performance with HVFA concrete is variable. Hand-finished flatwork is most susceptible. Class C fly ash shows slightly better resistance. Curing membranes may increase resistance.	Limit the level of fly ash in hand-finished flatwork (for example, sidewalks and driveways) exposed to deicing salts (ACI318 limits) - especially in late-fall placing. Where possible, ensure adequate drying period before first application of deicing salt. Pay special attention to the mix proportions (w/cm), air-void system, and finishing and curing practices when fly ash concrete is used in flatwork exposed to deicing salts.
-----------------------------------	--	--

*Unless indicated otherwise, a minimum amount of 15% fly ash is needed to achieve the desired properties. Optimum dosage levels are dependant on the composition of the fly ash, mix design, exposure conditions, and required service

5. Case Studies

As discussed earlier, fly ash has been used in practically all types of concrete applications from residential foundations to high-performance concrete for highway and marine structures, and high-strength concrete for high-rise construction. Fly ash is used in both ready-mixed and precast concrete, and also in pumped concrete, slipformed concrete, roller-compacted concrete, shotcrete, and controlled low-strength material. The following case studies have been selected as examples of some of the more demanding applications of fly ash concrete.

Using Fly Ash to Control Alkali-Silica Reaction— Lower Notch Dam, Ontario

The Lower Notch Dam (Figure 21) is perhaps one of the only major concrete structures that was constructed using a known reactive

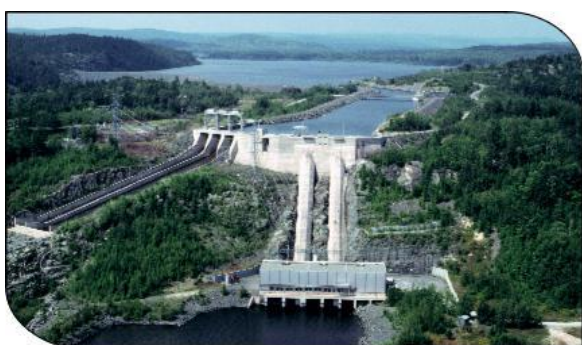


Figure 21: Lower Notch Dam, Ontario, Canada (Courtesy Ontario Power Generation)



Figure 22: Lady Evelyn Dam, Ontario, Canada.

greywacke aggregate and high-alkali cement with fly ash as the sole measure for preventing expansion and damage due to alkali-silica reaction, ASR (Thomas 1996). The dam, which was completed in 1969, is situated on the Montreal River at Lake Timiskaming in the Canadian province of Ontario. Testing prior to construction failed to identify the aggregate as reactive using the ASTM C289

Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method) and the ASTM C227 *Standard Test Method for Potential Alkali Reactivity of Cement*. However, the timely investigation of the nearby Lady Evelyn Dam (Figure 22) in 1965 implicated similar rock types from the Montreal River area in damaging ASR (this structure was eventually replaced). This prompted more detailed investigations of the aggregate intended for use in the Lower Notch Dam and testing in concrete confirmed the reactivity of the rock. Numerous highway structures (including 26 bridges) and hydraulic structures in this part of Ontario, which were constructed with similar aggregates, but without fly ash, have since shown damage due to ASR (Thomas 1996).

Testing at Ontario Hydro's Research Division indicated that expansion due to ASR with this aggregate could be prevented by using either a low-alkali cement or fly ash. The final decision was to use a combination of Class F fly ash combined with a high-alkali cement (one analysis during construction reported a cement alkali level of 1.08% Na₂Oe). A replacement level of 20% fly ash was used for the structural concrete in the powerhouse and 30% fly ash in the massive concrete structures (Thomas 1996). A visual inspection of the structure and examination of cores 25 years after construction revealed no evidence of ASR (Thomas 1996). A more recent inspection of the structure (2006) confirmed that there were no visible signs of ASR (that is no signs of expansion or cracking) 35 years after construction.

Using Fly Ash to Increase Chloride Resistance— St. Clair River Tunnel

The new St. Clair River Tunnel was constructed in 1993-1994 between Sarnia in Ontario and Port Huron in Michigan. The ground-water contained chlorides (4000 ppm) and sulfates (155 ppm), and



Figure 23: St. Clair river tunnel precast tunnel lining segments.

(Courtesy Hatch Mott MacDonald)



Figure 24: York University - computer science building.
(Courtesy www.pkphotography.com)

this environment, combined with hydrostatic heads of up to 35 m (115 ft) led to the inclusion of both chloride diffusion and permeability limits in the concrete specification for the precast tunnel lining segments. The requirements for the concrete were (Hart 1997):

- cementitious content from 400 to 550 kg/m³ (675 to 927 lb/yd³);
- w/cm ≥ 0.36 ;
- compressive strength ≥ 60 MPa (8700 psi) at 28 days;
- chloride diffusion coefficient, $Da \geq 600 \times 10^{-15}$ m²/s (6456 $\times 10^{-15}$ ft²/s) at 120 days; and
- water permeability, $k \leq 25 \times 10^{-15}$ m/s (82 $\times 10^{-15}$ ft/s) at 40 days.

The concrete was produced at a local ready-mixed concrete plant and delivered in a transit mixer to the precast plant. The concrete mixture used at the start of the production process contained 6% silica fume and 30% Class C fly ash with w/cm ranging from 0.29 to 0.32. This mix met specification including the chloride diffusion

Table 10: HVFA Concrete Mixture Proportions (kg/m³ (lb/yd³))

	Typical mix	Job mixes	
	30MPa (4350 psi)	25 Mpa (3625 psi)	30 Mpa (4350 psi)
Cement (Type I/Type 10)	380 (640)	150 (253)	170 (287)
Fly ash	0	150 (253)	170 (287)
Stone	1130 (1905)	1150 (1938)	1110 (1871)
Sand	716 (1207)	850 (1433)	800 (1348)
Water	171 (288)	135 (228)	135 (228)
w/cm	0.45	0.45	0.4

(Hopkins 2001)



Figure 24: York University - computer science building.
(Courtesy www.pkphotography.com)

coefficient at 120 days. RCPT values for slices cut from cores to include the back surface were less than 400 coulombs. Shortly after production began, the silica fume was eliminated from the mix and the majority of the tunnel lining segments produced for the project contained fly ash (25 to 35%) as the only SCM. The fly ash concrete met the strength and permeability limits but generally failed to meet the chloride diffusion coefficient at 120 days. However, testing of 3-year-old concrete cylinders (Thomas, 2001) indicated that the chloride diffusion coefficient would be met with extended curing. These cylinders had measured rapid chloride permeability values below 300 coulombs.

High-Volume Fly Ash Concrete - York University

The computer sciences building (Figure 24) at York University in Toronto, Ontario, was designed and constructed using the following green building practices:

- Energy-efficient building envelop;
- Natural illumination, ventilation and heating;
- Reduced resource consumption;
- Efficient land use;
- Reduced emissions; and
- Use of recycled materials.

In order to meet the last of the listed strategies high-volume fly ash (HVFA) concrete (with 50% fly ash) was used throughout construction (Hopkins 2001). The concrete used in the columns, walls and suspended slabs had a specified strength of 30 MPa (4350 psi) and that used in the slab-on-grade had a specified strength of 25 MPa (3625 psi). The maximum water-to-cementing-materials ratio (w/cm) was 0.45 and there was a requirement that the concrete receive a minimum of 7 days moist curing. The mixture proportions for the concrete mixes used are shown in Table 10. The fly ash used had an exceptional water-reducing effect, allowing the water content of the mix to be reduced by about 35 kg/m³ (59 lb/yd³) compared with the concrete producer's typical 30 MPa (4350 psi) mix without fly ash (also shown in Table 10). Figure 25 shows the strength development of the 30 MPa (4350 psi) HVFA concrete mix compared to the producer's typical 30 MPa (4350 psi) mix.

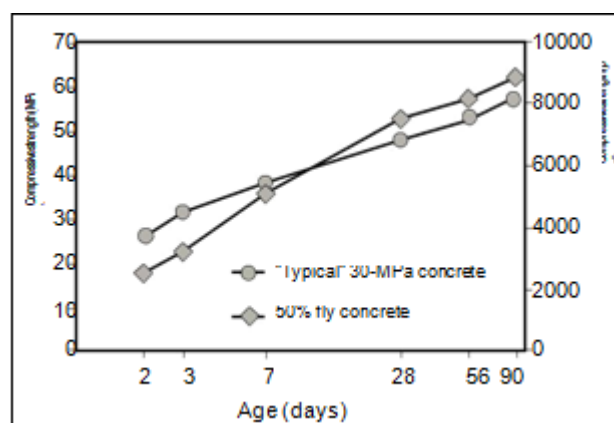


Figure 25: Strength development of HVFA concrete used at York University

No unusual problems were encountered with placing or finishing this concrete. It was generally observed that the concrete was relatively easy to place and finish. The use of

50% fly ash in the concrete did not impact the construction schedule. An early-age (plastic) cracking issue during hot windy weather was addressed through the use of an evaporation retardant and the expedient application of wet burlap (Hopkins 2001). The slump and strength of the concrete delivered to site was found to be reasonably consistent throughout the construction period (winter and summer).

Optimizing the Amount of Fly Ash in Concrete— Bayview High-Rise Apartment

The Bayview high-rise apartment complex was constructed in Vancouver between 1999 and 2001 and consists of a 30-story residential tower and approximately 3000 m² (3500 yd²) of commercial space (Busby and Associates 2002). The architect for this project worked with EcoSmart (a government-industry consortium promoting the use of high-volume fly ash concrete) to increase the level of fly ash used in this project. The owner and contractor were both willing to use higher volumes of fly ash provided this did not increase the cost or require changes in construction practices (for example, changing the construction schedule). Table 11 shows the different types of concrete and levels of fly ash used for this project.

The amount of fly ash was optimized on the basis of the requirements of the concrete specification, the construction schedule and the temperature. For example, the amount of fly ash was limited to 20% in the slabs on grade because they were placed in the winter. A 3-day tower cycle schedule was called for instead of the typical 5-day cycle and, because of stripping and finishing delays often associated with concrete with high levels of fly ash, the contractor limited the amount of fly ash used in the suspended slabs. The project was considered a great success (Figure 26). The amount of fly ash used was increased on average by 13% over the contractor's standard practice for this type of construction (Busby and Associates 2002).

Table 11: Concrete Requirements and Fly Ash Levels Used in the Bayview High-Rise Apartment

Element	Min. 28-day strength, MPa (psi)	Fly ash content (%)	w/cm
Parking slabs and slab bands	35 (5000)	33	0.4
Slab on grade—interior parking	25 (3600)	20	0.5
Slab on grade - exterior	32 (4600)	20	0.45
Core footing	30 (4350)	45	0.5
Other footings	25 (3600)	45	0.5
Shear walls and columns			
Foundation to 8 th floor	40 (5800)	33	0.45
8 th to 12 th floor	35 (5000)	33	0.45
12 th to 16 th floor	30 (4350)	33	0.45
16 th floor to roof and other walls	25 (3600)	33	0.45
Tower slabs	25 (3600)	15 to 25	
Toppings and housekeeping pads	20 (2900)	45	

(Busby and Associates 2004)



Figure 26: Bayview high-rise apartment. (Courtesy Ecosmart Foundation)

6. Summary

This publication discusses the impact of fly ash on the properties of concrete with a view to optimizing the level of fly ash used for a given application. The optimum amount of fly ash varies not only with the application, but also with composition and proportions of all the materials in the concrete mixture (especially the fly ash), the conditions during placing (especially temperature), construction practices (for example, finishing and curing) and the exposure conditions. Thus, the optimum fly ash content will vary on a case-by-case basis. Fly ash contents of up to 50% may be suitable for most elements provided the early-age strength requirements of the project can be met and provided that adequate moist-curing can be ensured. For flatwork, the level may be dictated by finishing requirements.

If adequate curing cannot be provided or if the concrete is exposed to freezing and thawing in the presence of deicer salts, the amount of fly ash should be limited (for example, ≤ 25%).

References

- [1] AASHTO M 295, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, American Association of State Highway and Transportation Officials, Washington, DC, 2007.
- [2] ACAA, "2005 Coal Combustion Product (CCP) Production and Use Survey," American Coal Ash Association, www.acaa-usa.org, 2006.
- [3] ACI Committee 116, *Cement and Concrete Terminology*.
- [4] ACI 116R-1-00, American Concrete Institute, Farmington Hills, Michigan, 2000, 73 pages.
- [5] ACI Committee 232, *Use of Fly Ash in Concrete*, ACI 232.2R-03, American Concrete Institute, Farmington Hills, Michigan, 1996, 41 pages.
- [6] ACI Committee 232, *Use of Raw or Processed Natural Pozzolans in Concrete*, ACI 232.1R-00, American

- Concrete Institute, Farmington Hills, Michigan, 2001, 24 pages.
- [7] ACI Committee 305, *Specification for Hot Weather Concreting*, 305.1-06, American Concrete Institute, Farmington Hills, Michigan, 2006, 12 pages.
 - [8] ACI Committee 318, *Building Code Requirements for Structural Concrete and Commentary*, 318-05, American Concrete Institute, Farmington Hills, Michigan, 2006.
 - [9] ASTM C150-07, *Standard Specification for Portland Cement*, American Society of Testing and Materials, West Conshohocken, PA, 2007.
 - [10] ASTM C151-05, *Standard Test Method for Autoclave Expansion of Hydraulic Cement*, American Society of Testing and Materials, West Conshohocken, PA, 2005.
 - [11] ASTM C227-03, *Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)*, American Society of Testing and Materials, West Conshohocken, PA, 2003.
 - [12] ASTM C289-03, *Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)*, American Society of Testing and Materials, West Conshohocken, PA, 2003.
 - [13] ASTM C595-07, *Standard Specification for Blended Hydraulic Cements*, American Society of Testing and Materials, West Conshohocken, PA, 2007.
 - [14] ASTM C618-05, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, American Society of Testing and Materials, West Conshohocken, PA, 2005.
 - [15] ASTM C672/C672M-03, *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*, American Society of Testing and Materials, West Conshohocken, PA, 2003.
 - [16] ASTM C1157-03, *Standard Performance Specification for Hydraulic Cement*, American Society of Testing and Materials, West Conshohocken, PA, 2003.
 - [17] ASTM C1012-04, *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*, American Society of Testing and Materials, West Conshohocken, PA, 2004.
 - [18] ASTM C1202-05, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, American Society of Testing and Materials, West Conshohocken, PA, 2005.
 - [19] ASTM C1293-06, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction*, American Society of Testing and Materials, West Conshohocken, PA, 2006.
 - [20] ASTM C1567-04, *Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)*, American Society of Testing and Materials, West Conshohocken, PA, 2004.
 - [21] Afrani, I., and Rogers, C., "The Effects of Different Cementing Materials and Curing on Concrete Scaling," *Cement, Concrete, and Aggregates*, Vol. 16 (2), 1994, pages 132 to 139.
 - [22] Anon, "An Investigation of the Pozzolanic Nature of Coal Ashes," *Engineering News*, Vol. 71, No. 24, 1914, pages 1334 to 1335.
 - [23] Atis, C.D., "High-Volume Fly Ash Abrasion Resistant Concrete," *Journal of Materials in Civil Engineering*, ASCE, Vol. 14, No. 3, 2002, pages 274 to 277.
 - [24] Atis, C.D., "High-Volume Fly Ash Concrete with High-Strength and Low Drying Shrinkage," *Journal of Materials in Civil Engineering*, ASCE, Vol. 15, No. 2, 2003, pages 153 to 156.
 - [25] Bamforth, P.B., "In-Situ Measurement of the Effect of Partial Portland Cement Replacement Using Either Fly Ash or Ground-Granulated Blastfurnace Slag on the Performance of Mass Concrete," *Proceedings of the Institution of Civil Engineers*, Part 2, Vol. 69, September, 1980, pages 777 to 800.
 - [26] Bamforth, P.M., "The Derivation of Input Data for Modelling Chloride Ingress From Eight-Year UK Coastal Exposure Trials," *Magazine of Concrete Research*, Vol. 51, No. 2, 1999, pages 87 to 96.
 - [27] Barrow, R.S., Hadchiti, K.M., Carrasquillo, P.M. and Carrasquillo, R.L., "Temperature Rise and Durability of Concrete Containing Fly Ash," *Proceedings of the Third International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, (Ed. V.M. Malhotra), ACI SP-114, Vol. 2, American Concrete Institute, Detroit, 1989, pages 331 to 347.
 - [28] Best, J. F., and Lane, R. O., "Testing for Optimum Pumpability of Concrete," *Concrete International*, V. 2, No. 10, Oct., 1980, pages 9 to 17.
 - [29] Bilodeau, A., Carette, C.G., Malhotra, V.M. and Langley, W.S., "Influence of Curing and Drying on Salt Scaling Resistance of Fly Ash Concrete," *Proceedings of the 2nd International Conference on the Durability of Concrete*, ACI SP-126, Vol. 1, Farmington Hills, MI, 1991, pages 201 to 228.
 - [30] Bilodeau, A., Zhang, M.H., Malhotra, V.M. and Golden, D.M., "Effect of Curing Methods and Conditions on the Performance of Fly Ash Concrete in Deicing Salt Scaling," *Proceedings of the Sixth CANMET/ACI/JCI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI SP-178, Vol. 1, American Concrete Institute, Farmington Hills, MI, 1998, pages 361 to 384.
 - [31] Bisailon, A., Rivest, M. and Malhotra, V.M., "Performance of High-Volume Fly Ash Concrete in Large Experimental Monoliths," *ACI Materials Journal*, Vol. 91, No. 2, 1994, pages 178 to 187.
 - [32] Bouzoubaa, N. and Lechemi, M., "Self-Compacting Concrete Incorporating High Volumes of Class F Fly Ash: Preliminary results," *Cement and Concrete Research*, Vol. 31, 2001, pages 413 to 420.
 - [33] Bouzoubaa, N., Tamtsia, B., Zhang, M.H., Chevrier, R.L., Bilodeau, A. and Malhotra, V.M., "Carbonation of Concrete Incorporating High Volumes of Fly Ash," *Proceedings of the Seventh CANMET/ACI International Conference on the Durability of Concrete*,
 - [34] ACI SP-234, American Concrete Institute, Farmington Hills, MI, 2006, pages 283 to 304.
 - [35] Busby and Associates, *Use of EcoSmart Concrete in the Bayview High-Rise Apartment, Vancouver, B.C.*, Busby and Associates Architects, www.ecosmartconcrete.com, 2002.
 - [36] CAN/CSA A3001-03, *Cementitious Materials for Use in Concrete*, Canadian Standards Association, Toronto, 2003, 318 pages.

- [37] CAN/CSA-A23.1-04/A23.2-04- *Concrete Materials and Methods of Concrete Construction /Methods of Test and Standard Practices for Concrete*, Canadian Standards Association, Toronto, 2004, 526 pages.
- [38] Carrette, G., Bilodeau, A., Chevrier, R.L. and Malhotra, V.M., "Mechanical Properties of Concrete Incorporating High Volumes of Fly Ash from Sources in the U.S.," *ACI Materials Journal*, Vol. 90, No. 6, 1993, pages 535 to 544.
- [39] Concrete Society, *The Use of GGBS and PFA in Concrete*, Technical Report No. 40, The Concrete Society, Wexham, Slough, 1991, 142 pages.
- [40] Cross, D., Stephens, J. and Vollmer, J., "Field Trials of 100% Fly Ash Concrete," *Concrete International*, September, 2005, pages 47 to 51.
- [41] Davis, R.E., Carlson, R.W., Kelly, J.W. and Davis, H.E., "Properties of Cements and Concretes Containing Fly Ash," *Journal of the American Concrete Institute*, Vol. 33, 1937, pages 577 to 611.
- [42] Dhir, R.K., "Near - Surface Characteristics of Concrete: Prediction of Carbonation Resistance," *Magazine Concrete Research*, 41, No. 148, 1989, pages 137 to 143.
- [43] Dunstan, E.R., *Fly Ash and Fly Ash Concrete*, Report No. REC-ERC-82-1, U.S. Bureau of Reclamation, Denver, 1984.
- [44] Dunstan, E.R., "A Possible Method for Identifying Fly Ashes That Will Improve the Sulfate Resistance of Concretes," *Cement, Concrete and Aggregates*, 1980, pages 20 to 30.
- [45] Dunstan, M.R.H. "Development of High Fly Ash Content Concrete," *Proceedings of the Institution of Civil Engineers*, Part 1, Vol. 74, 1983, pages 495 to 513.
- [46] Dunstan, M.R.H. "Fly Ash as the 'Fourth Ingredient' in Concrete Mixtures," *Proceedings of the Second CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI SP-91, Vol. 1, American Concrete Institute, Detroit, MI, 1986, pages 171 to 199.
- [47] Dunstan MRH, Thomas MDA, Cripwell JB, Harrison DJ., "Investigation Into the Long-Term In-Situ Performance of High Fly Ash Content Concrete Used for Structural Applications," *Proceedings of the Fourth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, Volume 1, ACI SP-132, American Concrete Institute, Detroit, 1992, pages 1 to 20.
- [48] Ellis-Don, "Leading Edge," *Edifice Magazine*, Ellis-Don Construction Ltd, London, Ontario, March, 1996, page 14.
- [49] Gebler, S., and Klieger, P., "Effect of Fly Ash on the Air-Void Stability of Concrete," *Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete*, ACI SP-79, Vol. 1, American Concrete Institute, Farmington Hills, MI., 1983, pages 103 to 142.
- [50] Gebler, S.H. and Klieger, P., "Effect of Fly Ash on the Durability of Air-Entrained Concrete," *Proceedings of the 2nd International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, ACI SP-91, Vol. 1, American Concrete Institute, Farmington Hills, MI, 1986, pages 483 to 519.
- [51] Ghosh, R.S. and Timusk, J., "Creep of Fly Ash Concrete", *ACI Journals*, Vol. 78, No. 5, Sep-Oct. 1981, pages 351 to 357.
- [52] Gifford, P.M., Langan, B.W., Day, R.L., Joshi, R.C. and Ward, M.A., "A Study of Fly Ash Concrete in Curb and Gutter Construction Under Various Laboratory and Field Curing Regimes." *Canadian Journal of Civil Engineering*, Vol. 14, 1987, pages 614 to 620.
- [53] Haque, M.N., Goplan, M.K., Joshi, R.C. and Ward, M.A., "Strength Development of Inadequately Cured High Fly Ash Content and Structural Concretes", *Cement and Concrete Research*, Vol. 16, 1986, pages 363 to 372.
- [54] Hart, A.J.R., Ryell, J. and Thomas, M.D.A. "High Performance Concrete in Precast Concrete Tunnel Linings, Meeting Chloride Diffusion and Permeability Requirements," *Proceedings of the PCI/FHWA International Symposium on High Performance Concrete*, October, 1997, pages 294 to 307
- [55] Helmuth, R., *Fly Ash in Cement and Concrete*, SP040, Portland Cement Association, Skokie, IL, 1987, 203 pages.
- [56] Ho, D.W.S. and Lewis, R.K., "Carbonation of Concrete Incorporating Fly Ash or a Chemical Admixture." *Proceeding of the First International Conference on the Use of Fly Ash, Silica Fume, Slag, and Other By-Products in Concrete*, ACI SP-79, Vol. 1, American Concrete Institute, Farmington Hills, MI, 1983, pages 333 to 346.
- [57] Ho, D.W.S. and Lewis, R.K. 1987. "Carbonation of Concrete and its Prediction." *Cement and Concrete Research*, Vol. 17, No. 3, pp. 489-504.
- [58] Hobbs D.W., "Carbonation of Concrete Containing PFA". *Magazine Concrete Research*, 40, No. 143, 1988, pages 69 to 78.
- [59] Hopkins, D.S., Thomas, M.D.A., Girn, G. and Munro, R., "York University uses High-Volume Fly Ash Concrete for Green Building", *Annual Conference of the Canadian Society for Civil Engineering*, CSCE, 2001.
- [60] Johnston, C., "Effects of Microsilica and Class C Fly Ash on Resistance of Concrete to Rapid Freezing and Thawing and Scaling in the Presence of Deicing Agents." *Concrete Durability*, ACI SP-100, Vol. 2, American Concrete Institute, Farmington Hills, MI, 1987, pages 1183 to 1204.
- [61] Johnston, C.D., "W/CM Code Requirements Inappropriate for Resistance to Deicer Salt Scaling." *Proceedings of the 3rd International Conference on the Durability of Concrete*,
- [62] ACI SP-145, American Concrete Institute, Farmington Hills, MI, 1994, pages 85 to 105.
- [63] Johnston, C.D., and Malhotra, V.M., "High-Strength Semi-Lightweight Concrete With up to 50% Fly Ash by weight of Cement", *Cement, Concrete, and Aggregates*, Vol. 9, No. 2, Winter, 1987, pages 101 to 112.
- [64] Joshi, R.C., Day, R.L., Langan, B.W., and Ward, M.A., "Engineering Properties of Concrete Containing High Proportions of Fly Ash and Other Mineral Admixtures", *Proceedings of the Second International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, Supplementary Papers, Madrid, Spain, 1986, pages 20-1 to 20-23.

- [65] Lane, R. O., and Best, J. F., "Properties and Use of Fly Ash in Portland Cement Concrete," *Concrete International*, V. 4, No. 7, 1982, pages 81 to 92.
- [66] Langley, W.S., Carrette, G.G. and Malhotra, V.M., "Strength Development and Temperature Rise in Large Concrete Blocks Containing High Volumes of Low-Calcium (ASTM Class F) Fly Ash." *ACI Materials Journal*, Vol. 89, No. 4, 1992, pages 362 to 368.
- [67] Langley, W.S. and Leaman, G.H., "Practical Uses of High-Volume Fly Ash Concrete Utilizing a Low Calcium Fly Ash." *Proceedings of the Sixth CANMET/ACI/JCI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI SP-178, Vol. 1, American Concrete Institute, Detroit, MI, 1998, pages 545 to 574.
- [68] Lewandowski, R. "Effect of Different Fly-Ash Qualities and Quantities on the Properties of Concrete". *Betonwerk und Fertigteil - Technik*, Nos 1 -3, 1983.
- [69] Majko, R.M., and Pistilli, M.F., "Optimizing the Amount of Class C Fly Ash in Concrete Mixtures", *Cement, Concrete, and Aggregates*, ASTM, Vol. 6, No. 2, Winter, 1984, pages 105 to 119.
- [70] Malhotra, V.M., "Superplasticized Fly Ash Concrete for Structural Applications." *Concrete International*, December, 1986, pages 28 to 31.
- [71] Malhotra, V.M., Zhang, M-H., Read, P.H. and Ryell, J. 2000. "Long-term mechanical properties and durability characteristics of high-strength/high-performance concrete incorporating supplementary cementing materials under outdoor exposure conditions." *ACI Materials Journal*, Vol. 97, No. 5, pp. 518-525.
- [72] Malhotra, V.M. and Mehta, P.K., *High-Performance, High-Volume Fly Ash Concrete*. Supplementary Cementing Materials for Sustainable Development Inc., Ottawa, Canada, 2005, 124 pages.
- [73] Manmohan, D. and Mehta, P.K., "Heavily Reinforced Shearwalls and Mass Foundations Built with "Green" Concrete." *Concrete International*, August, 2002, pages 64 to 70.
- [74] Marceau, M.L., Gajda, J., and VanGeem, M.G., *Use of Fly Ash in Concrete: Normal and High Volume Ranges*, PCA R&D Serial No. 2604, Portland Cement Association, Skokie, Illinois, 2002.
- [75] Marsh, B.K., Day, R.L. and Bonner, D.G., "Pore Structure Characteristics Affecting the Permeability of Cement Paste Containing Fly Ash." *Cement and Concrete Research*, Vol. 15, 1985, pages 1027 to 1038.
- [76] Matthews, J.D., "Carbonation of Ten-Year Old Concretes With and Without PFA", *Proceedings 2nd International Conference on Fly Ash Technology and Marketing*, London, Ash Marketing, CEBG, 398A, 1984.
- [77] Mehta, P.K., "Effect of Fly Ash Composition on Sulfate Resistance of Cement", *ACI Materials Journal*, Nov-Dec, 1986, pages 994 to 1000.
- [78] Mehta, P.K. "Performance of High-Volume Fly Ash Concrete in Hot Weather." *Innovations in Design with Emphasis on Seismic, Wind, and Environmental Loading: Quality Control and Innovations in Materials/Hot-Weather Concreting*, ACI SP-209, American Concrete Institute, Farmington Hills, MI, 2002, pages 47 to 52.
- [79] Mehta, P.K. and Langley, W.S., "Monolith Foundation, Built to Last a 1000 Years." *Concrete International*, July, 2000, pages 27-32.
- [80] Munday, J.G.L., Ong, L.T., and Dhir, R.K., "Mix Proportioning of Concrete with Pulverized Fly Ash-A Critical Review.", *Proceeding of the First International Conference on the Use of Fly Ash, Silica Fume, Slag, and Other By-Products in Concrete*, ACI SP-79, Vol. 1, American Concrete Institute, Farmington Hills, MI, 1983, pages 267 to 287.
- [81] Mustard, J.N. and MacInnis, C., "The Use of Fly Ash in Concrete by Ontario Hydro." *Engineering Journal*, December, 1959, pages 74 to 79.
- [82] Nagataki, S., Ohga, H. and Kim, E.K., "Effect of Curing Conditions on the Carbonation of Concrete with Fly Ash and the Corrosion of Reinforcement in Long Term Tests", *Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI-SP91, Vol. 1, American Concrete Institute, Farmington Hills, MI, 1986, pages 521 to 540.
- [83] Naik, T.R., and Ramme, B.W., "Setting and Hardening of High Fly Ash Content Concrete", *Proceedings of the Eighth International Ash Utilization Symposium*, Vol. 1, 1987, pages 16-1 to 16-20.