York University uses High-Volume Fly Ash Concrete for Green Building

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ABSTRACT: This paper discusses the use of high levels of fly ash in concrete as part of a “Green Building” at York University in Toronto. In most of the concrete mixes used for the building, 50% of the Portland cement was replaced with CSA A23.5 type CI fly ash, an industrial by-product, from Ontario. Despite the significant reduction in the cement content, the concrete produced comfortably met the specified strength requirements, was easy to place and finish, and its use had no impact on the construction schedule. Such concrete may be suitable for many other commercial or residential construction applications, although the material does require some special consideration (e.g. regarding curing) especially when used in a severe exposure condition. This paper discusses the environmental, economic and technical issues of using high contents of fly ash in concrete construction.

1. INTRODUCTION

Part of the “Green Building Strategy” of a recent construction project at York University in Toronto included the use of “Green Products”. Such products are defined as those with one or more of the following characteristics: (i) embodying low energy costs, (ii) being of high durability and low maintenance, (iii) containing a large proportion of recycled or recyclable materials. In response to York Universities sustainability initiatives, the Architectural Team for this building with included (Van Nostrand DiCAstri Architects and Busby + Associates Architects Ltd. in Joint Venture), and their structural consultants (Yolles) proposed the use of 50% fly ash concrete where possible. Fly ash is an industrial by-product from coal-fired electricity generating stations and, as such, represents a material that meets characteristics numbered (i) and (iii) above for a “Green Product”. It could also be argued that the appropriate use of fly ash in concrete meets the second criterion in that the resulting concrete will have enhanced long-term durability.

Fly ash has a long history of use in concrete construction; however, it is normally used to partially replace Portland cement at relatively modest levels of between 15 to 25% (by mass). The concrete used in this building used fly ash (from Ontario generating stations) to replace 50% (by mass) of the Portland cement component of the concrete. This represents further significant environmental benefits related to the reduced use of Portland cement, the production of which requires significant energy and results in

CO_2 emissions. The paper discusses the use of high-volume fly ash concrete in the construction of this building and makes particular emphasis to its role in "sustainable concrete construction".

2. FLY ASH

Fly ash, a by-product of burning pulverized coal in thermal generating stations, is a finely divided, amorphous alumino-silicate that reacts at normal temperature with calcium hydroxide to produce calcium-silicate hydrates (C-S-H) with cementitious properties; i.e. it is a pozzolanic material. As such, fly ash is a valuable resource to the construction industry as it can be used together with Portland cement to produce concrete. Fly ash will react with the calcium hydroxide ($Ca(OH)_2$) liberated by the normal hydration of Portland cement producing additional cementitious material in the hardened concrete. The potential for using fly ash in this manner has been known almost since the start of the last century (Anon, 1914) although it wasn't until the mid-1900's that significant utilization of fly ash in concrete began (e.g. Bureau of Reclamation, 1948). The last 50 years has seen the use of fly ash in concrete grow dramatically with current usage in the United States being somewhere in excess of 6 million tonnes per annum (Manz, 1993). This increased usage has been accompanied by a great deal of applied and fundamental research culminating in many thousands of technical papers providing testament to the fact that the appropriate use of fly ash in concrete can result in numerous technical and economic benefits. Despite this, the use of fly ash is often restricted by concrete specifications, either by total prohibition or by limiting the amount that can be used. A good example of this is the ACI Building Code (ACI 318), which limits the amount of fly ash to a maximum of 25% by mass of the total cementitious material.

Many workers have demonstrated that fly ash can be used at much higher replacement levels (e.g. > 40%) to produce concrete with good mechanical properties and excellent durability. Although the use of such levels of fly ash has generally been restricted to special applications such as roller-compacted concrete or large monolithic pours requiring temperature control, it has been demonstrated that levels of between 40 to 60% fly ash can be successfully used in normal structural concrete (Dunstan et al, 1992). However, it should be noted that concrete with high levels of fly ash displays somewhat different characteristics than plain Portland cement concrete and may require special consideration (e.g. with regard to curing and early-age strength development), especially when used at low ambient temperatures. It is perhaps for this reason that specifications (e.g. ACI 318) have been reluctant to permit higher levels of fly ash to be used for general concreting purposes. This is a pity since concrete properly produced with high levels of fly ash can have many technical advantages over normal concrete, particularly with regards to long-term durability in certain environments. Furthermore, the use of high levels of fly ash is beneficial in environmental terms as it utilizes an industrial by-product and results in reduced consumption of Portland cement.

The use of fly ash in concrete does require some special considerations and these become more important as the proportion of fly ash in the mix increases. Although certain fly ashes exhibit some cementitious properties, the main contribution to the hardened concrete properties results from the pozzolanic reaction of the fly ash with the $Ca(OH)_2$ released by the Portland cement. This reaction typically occurs more slowly than cement hydration reactions and consequently fly ash concrete requires more attention to be paid to moist curing during early ages. Also, because concrete containing fly ash gains strength more slowly at early ages (e.g. up to 7 days) compared with plain Portland cement concrete without ash, it is often necessary to target a higher standard 28-day strength (or lower water-cementing materials ratio) when early strength gain is a consideration (e.g. for form stripping).

3. YORK UNIVERSITY'S GREEN BUILDING

3.1 General

The Computer Science Building at York University in Toronto, Ontario, was designed and constructed with an holistic view towards sustainable construction; the following "green" building practices were incorporated as part of the whole process (Anon, 2001):

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

It has been estimated (Anon, 2001) that the combination of these strategies will result in reductions in greenhouse and acid gas emissions of more than 85,000 tonnes over the 75-year design life of the building. This paper only deals with the use of fly ash in the concrete, which fits into the last category listed; i.e. the use of recycled materials.

3.2 **Use of Fly Ash**

The fly ash used for the project was "Northern Ash" which is produced from a blend of fly ash from the Atikokan and Thunder Bay coal-fired electrical generating stations in Northern Ontario. The chemical composition of the fly ash is given in Table 1 and it meets all the requirements of a Type CI fly ash according to CSA A23.5, the national specification covering "Supplementary Cementing Materials".

Table 1 Chemical Analysis of Northern Ash

Oxide	**%**	**Oxide**	**%**
SiO_2	45.4	K_2O	0.59
Al_2O_3	20.2	Na_2O	6.79
Fe_2O_3	4.31	SO_3	1.48
CaO	13.7	LOI	0.59
MgO	2.86		

There are three coal-fired stations in southwestern Ontario that also produce fly ash. However, these stations are only operated during peak load times and the intermittent operation of the boilers renders the resulting fly ash generally unsuitable for concrete construction (i.e. the residual carbon content of the fly ash is too high).

3.3 **Trial Mixes**

Prior to construction a number of trial concrete mixes were conducted to examine the properties of the concrete with high levels of Northern Ash and to compare them with regular concrete (i.e. with no fly ash) of a comparable strength grade. Details of just three of these mixes are reported here, the mix proportions being given in Table 2.

Table 2 Proportions (kg/m^3) for Trial Mixes

	Mix 1	**Mix 3**	**Mix 4**
Cement (T10)	380	145	163
Northern Ash	0	145	163
Stone	1130	1130	1130
Sand	716	889	854
Water	171	131	130
W/C	0.45	0.45	0.40
WRA*	74	74	74

*Water-reducer (mL per 100 kg cementitious)

Test data from these trial mixes are presented in Table 3.

Table 3 Fresh Properties of Trial Mixes

	Mix 1	**Mix 3**	**Mix 4**
Air (%)	1.5	2.0	1.9
Initial slump (mm)	120	120	110
Slump at 45 min (mm)	95	80	80
Initial set (min)	240	275	250
Bleed water (ml/kg)	0.49	0.04	0

It was observed that the use of 50% affected a large reduction in the water demand of the concrete. This allowed a 40-kg/m^3 reduction in the water content of the concretes with fly ash, whilst maintaining the same slump as the control mix with no fly ash (all mixes having the same dosage of water-reducing admixture). Mixes cast with this reduced water content exhibited no bleeding. Mix #3 was produced with the same water-cementing materials ratio (W/CM = 0.45) as the control mix (Mix #1) and this resulted in a significant reduction in the cementitious material content (cement + fly ash) of the mix, i.e. from 380 kg/m^3 cement to 290 kg/m^3 cement + fly ash. Mix #4 was cast with a slightly lower W/CM (= 0.40) and this resulted in a cementitious material content of 325 kg/m^3 (which is still substantially less than the control mix, Mix #1).

Compressive strength data to the age of 90 days are shown in Figure 1. Mix #4 showed very similar strength development as the control mix between 3 and 28 days. Mix #3 showed lower strength at all ages. These data would suggest that a lower W/CM is required for mixes with 50% Northern Ash in order to ensure strength parity with concrete produced without the fly ash. This is typical for fly ash concrete especially at higher levels of replacement. However, the observed behaviour of the concretes beyond 28 days was not expected. Normally the long-term strength gain is improved by the incorporation of fly ash and proportionally greater strength increases would be expected beyond 28 days. This was not the case with the trial mixes as the control mix exhibited the highest degree of strength gain between 28 and 90 days.

In addition to strength tests, concrete samples were also prepared for testing according to the ASTM C 1202 test procedure, which is commonly known as

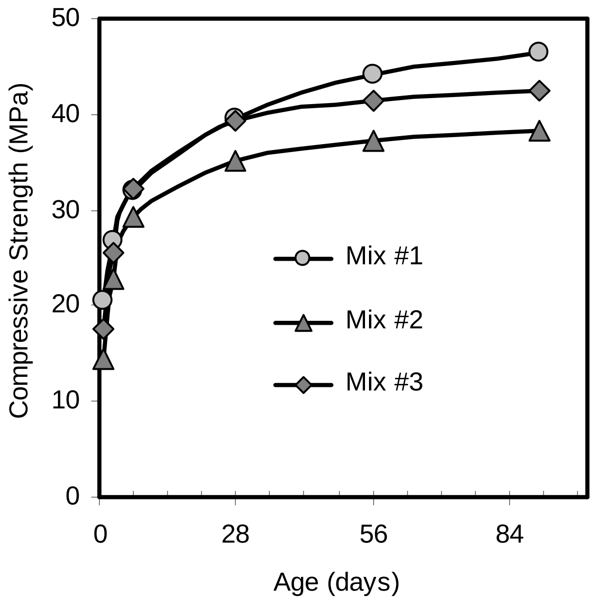

Fig 1 Strength Development of Trial Mixes

the "rapid chloride permeability test". The results at 30 days of age are presented in Table 4.

Table 4 ASTM C 1202 Results for Trial Mixes

	Mix 1	**Mix 3**	**Mix 4**
RCPT (Coulombs)	2950	360	300

Specimens from these mixes were also cast for other long-term durability tests.

3.4 **Concrete Production**

The specified strength of the concrete used was 30 MPa for columns, walls and suspended slabs and 25 MPa for the lower slab-on-grade. The maximum water to cementitious ratio was 0.45 (for the 30-MPa concrete) and the specification called for a minimum of 7 days moist curing. Table 5 shows the proportions of the job mixes.

Table 5 Proportions (kg/m^3) for Job Mixes

	25-MPa	**30-MPa**
Cement (T10)	150	170
Northern Ash	150	170
Stone	1150	1110
Sand	850	800
Water	135	135
W/C	0.45	0.40

A water-reducing admixture was added to all mixes and a retarding-admixture was added during the warmer summer temperatures.

The producer opted to supply the concrete at a lower W/CM than that specified. Results from quality control tests (slump and strength) performed on site-produced concrete samples, are shown in Table 6; these data are limited to mixes that contained a retarding admixture. It can be seen that the specified 28-day strengths were met comfortably. Indeed, the strength of the nominally 30-MPa mix was exceeded by a considerable margin as a result of the producer's decision to provide the concrete at lower W/CM.

Table 6 Results from QC Tests on Job Mixes

		25-MPa	**30-MPa**
Slump (mm)	No. of Test	15	49
	Max	140	130
	Min	70	50
	Mean	**101**	**89**
	SD	21	21
	COV	21%	23%
7-day Strength (MPa)	No. of Test	15	49
	Max	32.6	43.4
	Min	20.6	22.0
	Mean	**26.0**	**35.8**
	SD	4.4	4.2
	COV	17%	12%
28-day Strength (MPa)	No. of Test	8	20
	Max	40.2	50.5
	Min	28.7	36.2
	Mean	**32.4**	**44.5**
	SD	3.6	3.8
	COV	11%	9%

The results in Table 6 show that coefficient of variation for the strength tests conducted at 28 days was between 9% and 12%. This is well within accepted limits for ready-mix concrete and indicates a good level of quality control and material uniformity.

No unusual problems were encountered with placing or finishing this concrete. Indeed, 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 cracking issue with flat work during hot windy weather, was addressed through the use of an evaporation retardant and curing with wet burlap. Although concrete without 50% fly ash can also experience premature cracking in extreme drying conditions, the 50% fly ash mixture produced very little bleed water and probably warrants extra care to

ensure that the surface is kept moist prior to the application of curing procedures.

3.5 **Field Trial Tests**

In addition to the standard quality control tests discussed above, samples of the 30 MPa concrete were cast at the concrete producer's site for further tests including a suite of testing at the University of Toronto. As a comparison, samples were also cast from a typical 30 MPa concrete mix without fly ash. This mix had a cementitious materials content of 340 kg/m^3, which was comprised of 100% Type 10 Portland cement, and a W/CM of approximately 0.45.

Strength data for these field trial mixes are shown in Figure 2. The mix with 50% fly ash shows reduced early-age strength compared with the control, but the strength at 28 days and later is greater. This is more typical of established trends for fly ash than those shown earlier for the trial mixes (Fig. 1).

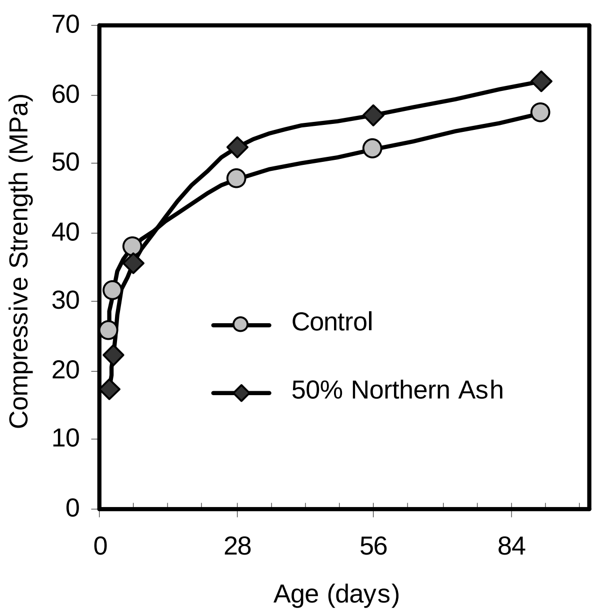

Fig 2 Strength of Field-Trial Mixes

Concrete slabs delivered to the University of Toronto at an age of 1 day were either given no further curing or were stored in the fog room for an additional 2 or 6 days to provide a total moist-curing period of 1, 3 or 7 days. These slabs were then stored in the laboratory until test. The testing carried out includes a whole suite of tests aimed at characterizing the pore structure of the concrete and its permeability to vapour, fluid and ionic transport. Only data from the "rapid chloride permeability test" are reported here, and these are given in Table 7 for concretes that were approximately 6 months old at the time of test.

Table 7 ASTM C 1202 Results for Field Trial Mixes

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

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

4. **DISCUSSION**

The successful use of concrete containing 50% fly ash for the Computer Science Building at York University demonstrates that such material can be used in regular commercial concrete construction without any major changes to normal construction practices or scheduling. Not only did the concrete have excellent fresh and hardened properties (e.g. workability and strength), it was reasonably consistent throughout the construction period (summer and winter). Furthermore, the concrete displayed a very low permeability, as measured by the ASTM C 1202 procedure.

The incentive to use concrete with high levels of supplementary cementing materials (particularly fly ash and slag) is growing as a result of environmental pressures. Concrete is the most widely used construction material in the world and the production of its principal binding component, Portland cement, results in considerable greenhouse gas emissions. Indeed, for every tonne of Portland cement manufactured, just less than 1 tonne of CO_2 is produced and liberated to the atmosphere. The cement industry has been very responsive to environmental issues, but the CO_2 production is an unavoidable consequence of the manufacturing process (i.e. calcination of limestone). The use of high volumes of fly ash (or other pozzolans or slag) can significantly reduce the amount of Portland cement used in concrete and help address problems associated with CO_2 emissions. Despite this more than 80% (or 4 Mtonnes per annum) of the fly ash produced at generating stations across Canada is landfilled. Better incentives are clearly required to encourage owners and engineers to use greater proportions of supplementary cementing materials in concrete, consistent with sound engineering practice.

There has been a recent surge in interest in the use of high levels of fly ash in concrete in the Greater Vancouver Regional District (GVRD) of Canada. A collaboration between GVRD, various Federal Government bodies and local industry spawned the EcoSmart™ Concrete Project, which has as its principal objective the reduction of greenhouse gas through the use of concrete containing the "maximum amount of supplementary cementing material, consistent with construction requirements". There are now a number of significant construction projects in the Greater Vancouver area that are using high volume fly ash concrete in the Greater Vancouver area (www.ecosmart.ca). A recently completed example is the University of British Columbia's Liu Centre for the Study of Global Issues (Seabrook and Campbell, 2000).

Although demonstration projects such as the Liu Centre and other projects in Vancouver, and the Computer Science Building at York University will help promote the wider use of high levels of fly ash in concrete, further initiatives are required if full exploitation of this technology is to be realized. Firstly, institutional barriers have to be removed. For example, national and provincial specifications that place blanket limits on the maximum allowable replacement level need to be removed. Such specifications would better serve the owner, the public and the construction industry if they controlled the use of fly ash (and other pozzolans and slag) through the imposition of appropriate performance criteria. Secondly, the construction industry, particularly the engineering community, needs to be educated on the properties of supplementary cementing materials and how they influence the properties of concrete. This includes developing an understanding of how fly ash varies between different sources and how to deal with these differences when developing a concrete to meet specific requirements. Thirdly, there needs to be an incentive for owners, contractors and engineers to fully investigate the potential for the use of high levels of supplementary cementing materials in concrete. This could happen through an extension of projects like Ecosmart™ across the whole of Canada.

Of course, the incorporation of high levels of fly ash into a concrete mix is not sufficient to ensure satisfactory performance. The concrete produced for the project discussed here had other noteworthy characteristics including the use of a high quality fly ash, low water-cementing materials ratio (W/CM), low water content, and provision of adequate curing. Previous studies have demonstrated that concrete of inferior quality may not be improved by the addition of fly ash. For example, poorly cured concrete of relatively low strength, carbonates very rapidly if high levels of fly ash are present (Thomas and Matthews, 2000). Also, it has been shown that the incorporation of fly ash into lean concrete (i.e. concrete with low cementitious content) leads to inferior performance in freezing and thawing environments (Whiting, 1989).

In order to achieve the full benefits that fly ash has to offer, one must take full advantage of its ability to reduce the water content of the concrete and resist the temptation to fully exploit this by making a proportional reduction in the cementitious material content of the mix (i.e. maintaining the W/CM). Although, the W/CM plays an important role in defining the pore structure of the concrete, it is the unit water content (W) that sets the total amount of pore space. The combination of a low W, low W/CM and a high volume of fly ash (as part of CM) will produce a concrete with a very low porosity and an extremely refined pore structure (i.e. very fine pores, high tortuosity and low connectivity), thereby producing a low permeability. This was evident from the RCPT data for the laboratory and field trial mixes. Other research has shown that concrete with these same characteristics has an exceptionally high resistance to chloride ion penetration also (Thomas and Matthews, 1996).

Another point worthy of mention concerns the fact that fly ash in North America can display a very wide range in terms of chemical, mineralogical and physical properties depending on the source of coal and conditions within the boiler of the generating station. Consequently, every source of fly ash needs to be adequately characterized prior to use in concrete. For example, the fly ash used here has a moderate calcium content and high alkali content and this is likely to contribute to the reactivity of the material and promote a faster strength gain at early ages than may be observed with a fly ash of lower reactivity.

Finally, a comment needs to be made about the use of high-range water reducers (a.k.a. super-plasticizers) in concrete containing high levels of fly ash. A substantial effort to promote the use of high-volume fly ash concrete has been made by CANMET over the past decade (e.g. Malhotra, 1994). The CANMET system may be characterized by relatively high fly ash replacement levels (typically 55 to 60%), low water-cementitious material ratio (in the range of W/CM = 0.30) and very low water contents (typically around 120 kg/m^3). Such a mix requires large doses of superplasticizer to achieve an acceptable workability. Whilst the authors of the current paper do not disagree that the use of a high-range water reducer to achieve even lower water contents than that used for the production of concrete for the York University building would result in even better durability properties, many (indeed, most) concrete applications do not require such high levels of performance. For the York University project, the use of a normal-range water reducer was more than sufficient to produce a concrete with good consistency in the plastic state and very low permeability in the hardened state.

For applications where concrete is exposed to very aggressive environments (e.g. structures exposed to deicing salts, seawater, sulphate or acidic groundwaters) a high level of resistance to the penetration of deleterious agents can be achieved through the combined use of high volumes of fly ash, superplasticizers (to achieve very low water contents) and silica fume. This has been discussed elsewhere (Thomas and Evans, 1997; Thomas et al, 1999).

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