Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Special Technical Proceedings ed. P Claisse, E Ganjian, F Canpolat and T Naik
ISBN 978-1-4507-1488-4 http://www.claisse.info/Proceedings.htm

Optimizing Fly Ash Content for Sustainability, Durability, and Constructability

Michael D.A. Thomas

University of New Brunswick, Department of Civil Engineering, P.O. Box 1400, Fredericton, NB, E3B 5A3, Canada, E-mail: <mdat@unb.ca>.

ABSTRACT

It is fairly well established that fly ash can improve many of the properties of fresh and hardened concrete as well as reduce the greenhouse gas (GFG) footprint associated with the use of portland cement. However, the use of fly ash at higher replacement levels may produce some undesirable properties such as a slower set time and strength development or increased carbonation or salt scaling. Consequently there is a need to optimize the fly ash content of concrete for different applications. This paper discusses how the optimum the level of fly ash is dependent on the properties of the fly ash, the performance requirements for the fresh and hardened concrete, the climatic conditions during construction and the exposure conditions and durability requirements during service. In many cases, the optimum level of fly ash may be 40% or more.

INTRODUCTION

The potential for using fly ash as a supplementary cementing material (SCM) in concrete has been known almost since the start of the last century [Anon 1914] although it wasn't until the mid-1900s, following the pioneering research conducted at the University of California, Berkeley [Davis et al. 1937], that significant utilization of fly ash in concrete began with the construction of the Hungry Horse Dam in Montana [USBR 1948]. 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.A. 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 even 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 et al. 2002].

There are many incentives for using fly ash at increasing levels of replacement as the use of fly ash improves many of the fresh and hardened properties of concrete, including durability, often reduces the cost of concrete and the life-cycle cost of structures, and leads to many environmental benefits including, reduced landfill, by-product utilization, and reduced CO_2 emissions resulting from the lower portland cement clinker content in fly-ash concrete. Increasing the amount of fly ash in concrete is not without shortcomings. At high replacement 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 illustrates how some aspects of concrete performance are improved by fly ash whereas others are impaired.

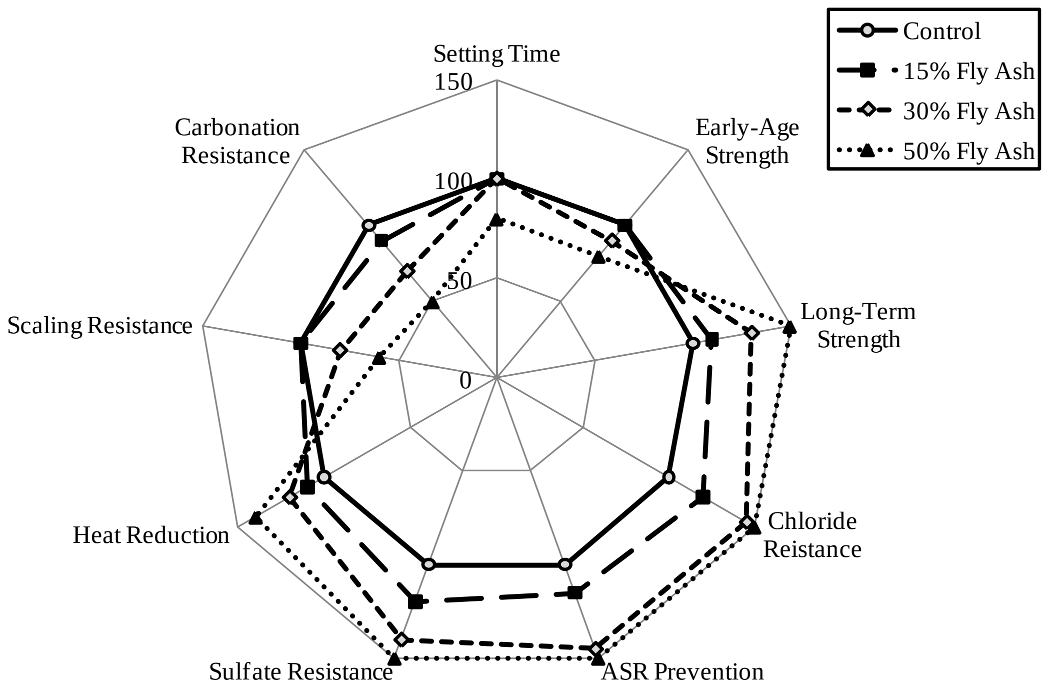

Fig. 1. Performance of Fly-Ash (Class F) Concrete Relative to Portland-Cement Concrete (PC Concrete performance = 100, values for fly ash concrete > 100 indicate improved performance and < 100 indicate reduced performance)

For any given situation there will be an optimum amount of fly ash that can be used 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. For example, the optimum fly ash content for a sidewalk slab that is placed in the late Fall and that will be exposed to de-icing salts, may be 15% or less, whereas the optimum content for a large pile placed in a saltwater environment during the summer may be 50% or more.

SUSTAINABILITY & FLY ASH

Although fly ash is produced from coal-burning electricity generation (a major CO_2 emitter), it is considered to be CO_2-neutral because it is a by-product of power generation and would have to be disposed of if it could not be utilised. Fly ash, like other SCM's, partially replaces portland cement in concrete, thereby reducing the CO_2 emissions associated with the manufacture of portland cement clinker. It is often stated that the manufacture of portland cement clinker releases approximately 1 tonne of CO_2 for each tonne of clinker produced.

About half of this CO_2 is due to the calcination of limestone ($CaCO_3 \xrightarrow{heat} CaO + CO_2$) in the kiln and the other half is released from burning fuel to heat the kiln. Although, the CO_2 resulting from calcination is inevitable, the cement industry has strived to make the process more energy efficient in the last few decades and CO_2 associated with the fuel may be as low as 0.25 tonne per tonne of clinker in the most efficient plants burning alternative fuels. Consequently, the average CO_2 production per tonne of clinker is now below one tonne (~ 0.9 tonne worldwide), and likely to decrease further as less efficient older kilns are replaced. Despite the best efforts of the industry, portland cement clinker production remains one of the major CO_2 emitters contributing an estimated 7% of the global GHG.

If fly ash is used to replace portland cement on a 1:1 basis, the estimated 15 million tons of fly ash used annually in the United States, may be considered to reduce CO_2 emissions by over 13 million tons.

In addition to reducing CO_2 emissions, the use of fly ash contributes to the sustainability of concrete by reducing the amount of waste that goes to landfill and the amount of raw materials consumed by cement manufacture, and by extending the life of concrete structures due to the improved durability of fly ash concrete.

DURABILITY & FLY ASH

Table 1 presents a general summary of the effect of fly ash on the properties of concrete. It is well established that the use of fly ash improves many of the durability properties of concrete, such as an increased resistance to chloride ingress and sulfate attack (Class F), and a reduced risk of alkali-silica reaction (ASR) and delayed ettringite formation (DEF). However, all fly ashes are not equally effective in these roles and high-calcium Class C fly ashes have to be used at higher levels of replacement to control ASR and may actually render concrete less resistant to sulfate attack in some conditions.

Furthermore, fly ash is not a panacea for all forms of deterioration and its use, especially at high replacement levels may increase the risk of carbonation-induced corrosion and may increase the susceptibility of concrete to de-icer salt scaling.

The increased risk of carbonation in fly ash concrete is generally a concern when high levels of fly ash are used in low grade, poorly-cured concrete, with low cover depths over the steel. The increased susceptibility of fly ash concrete to carbonate can be compensated for by extending the period of moist curing in conditions conducive to carbonation and by ensuring that the specified strength and cover are achieved.

The risk of scaling is also usually a concern only when relatively high levels of fly ash are used. 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.
- The use of curing compounds (membranes) reduces scaling of fly ash concrete

Table 1. Effect of Fly Ash on the Properties of Concrete [modified from Thomas, 2007]

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, and has 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 trowel finishing.
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 or using set accelerator 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 ≥ 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) portland cement, 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 portland cement (Type III or HE), or silica fume to compensate for reduced early-age strength. Consider using temperature-matched curing to evaluate 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, especially for larger elements.
Permeability and chlorides	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)
Risk of 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 (≥ 40%)	If a reactive aggregate is being used, Class F fly ash should be used, if available. Otherwise 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 (e.g. ASTM C 1293 or 1567).

Table 1. continued

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 C 150) cement or a Type MS or HS hydraulic cement (ASTM C 1157). Sulfate resistance may be reduced by Class C fly ashes. Resistance to cyclic immersion in sodium sulfate solution and drying has been shown to be relatively unaffected by up to 40% fly ash.	Use Class F fly ash. Test cement – fly ash combinations using ASTM C 1012. Do not use Class C fly ash as the sole method of prevention – if Class F fly ash is not available – test Class C fly ashes in combination with other SCMs (e.g. silica fume) using ASTM C 1012.
Risk of delayed ettringite formation	Reduced. Deleterious expansion of heat-cured concrete can be prevented by sufficient levels of replacement (≥ 25%). Class F may be slightly more efficient than Class C in this regard.	Limit concrete temperature (< 70°C). Use 25% or more fly ash (preferably Class F)
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 – 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.

- The results from laboratory scaling tests [ASTM C 672] 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 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.
- Scaling problems with fly ash concrete in the field are generally limited to "hand-placed" flatwork such as sidewalks and driveways, especially when high replacement levels are used and/or when proper placing and finishing procedures are not followed.
- The risk of scaling on formed or slipformed surfaces is low even when relatively high replacement levels are used. As the fly ash content of concrete increases, the scaling resistance of the surface is more sensitive to poor construction practices compared to portland cement concrete which is more robust in this regard.

CONSTRUCTABILITY & FLY ASH

The longer set time and slower strength gain of concrete containing fly ash, especially at higher replacement levels, can present problems to contractors in some circumstances. For example, if the setting time is extended this will likely result in a delay in finishing a slab that requires a trowel finish and joint-cutting slabs and pavements, and may lead to an increase in the risk of plastic shrinkage cracking. Slower early-age strength gain can increase the time until prestressing strands can be cut or post-tensioning tendons can be released, and also delay form stripping times, thus reducing productivity and lengthening the construction schedule.

Although it may be necessary to reduce the fly ash content of concrete when such issues are critical, the setting behaviour and early-age strength development can be compensated for to a certain extent by using chemical admixtures, using high-early strength cement (Type HE), adding silica fume, adjusting mix proportions or other means.

Table 2 shows data from the author's laboratory showing how a set accelerator can be used to partially offset the slower setting behaviour of fly ash concrete (W/CM = 0.42). It becomes more challenging to accomplish this at low temperatures and high fly ash contents, and it may be necessary to use heated water and/or Type HE cement in combination with an accelerator under such circumstances.

Table 2. Effect of Set Accelerator on Initial Set (h:m) of Fly Ash Concrete

Temp (°C)	Admix. Dose	Control	30% Fly Ash	50% Fly Ash
20	None	4.39	5.01	6.15
	Moderate	3.20	4.11	5.23
	High	2.42	3.21	4.25
10	None	6.05	6.59	9.22
	Moderate	4.12	5.06	7.01
	High	3.06	4.13	5.43

Figure 2 shows data from the author's laboratory indicating how adjusting the materials and mix proportions can offset the low early-age strength of concrete with a high level (50%) of fly ash. The reduction in w/cm was achieved here by taking advantage of the water reduction attributed to the fly ash (approximately 15% with 50% fly ash in this case) and by incorporating a superplasticer to achieve a further 15% reduction in the water content. Further reductions in w/cm can be achieved by raising the total cementitious material content, but this could be deemed to be counterproductive if the incentive for using fly ash is to reduce the clinker content.

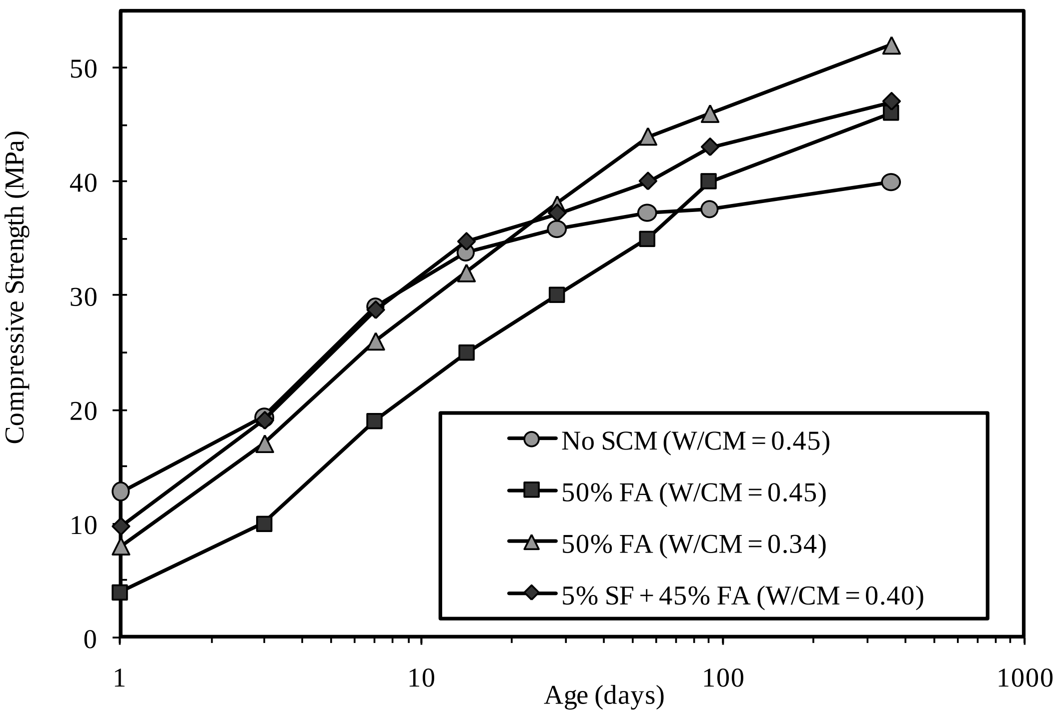

Fig. 2. Strength Development of HVFA Concretes

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 3 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.

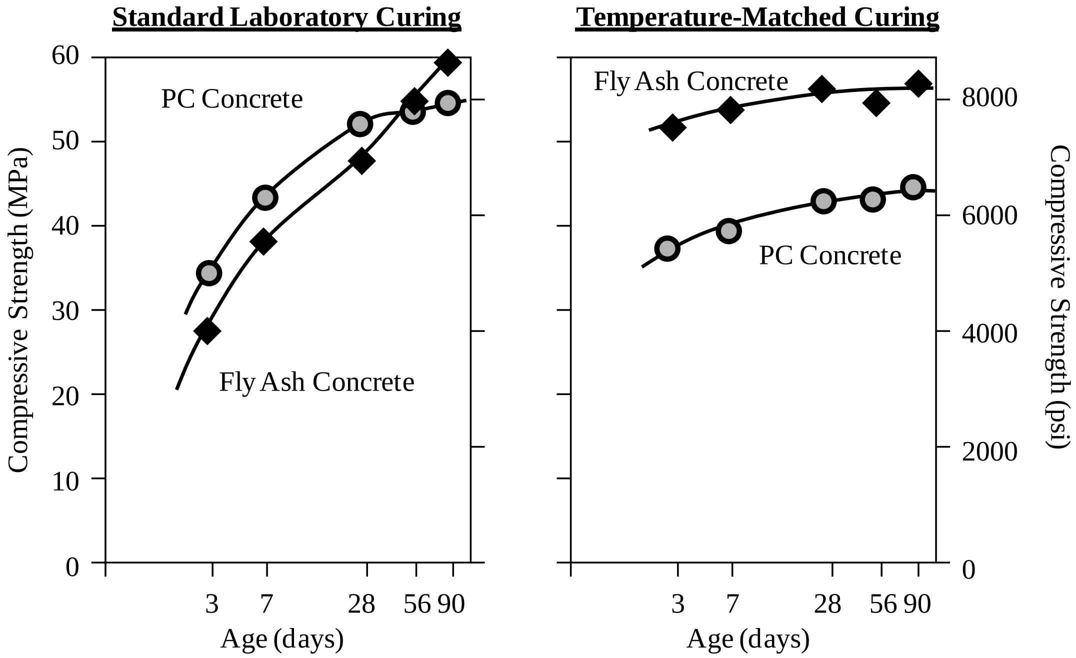

Fig. 3. Effect of Temperature-Matched Curing on the Strength Development of Concrete with and without Fly Ash [modified from Bamforth, 1980]

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 a low temperatures.

OPTIMIZING THE FLY ASH CONTENT OF 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 of the concrete, 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 1 provides a summary of how fly ash, when used at moderate to high levels of replacement (for example, 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 elements 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 et al. (2003) suggest 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.

CASE HISTORY – OPTIMIZING FLY ASH CONTENT

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 m^2 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 3 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. 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 3. Concrete Requirements and Fly Ash Levels Used in the Bayview High-Rise Apartment [Busby and Associates 2002]

Element	Min. 28d strength, MPa	Fly ash content (%)	Maximum w/cm
Parking slabs and slab bands	35	33	0.40
Slab on grade – interior parking	25	20	0.50
Slab on grade – exterior	32	20	0.45
Core footing	30	45	0.50
Other footings	25	45	0.50
Shear walls and columns			
Foundation to 8th floor	40	33	0.45
8th to 12th floor	35	33	0.45
12th to 16th floor	30	33	0.45
16th floor to roof and other walls	25	33	0.45
Tower slabs	25	15 to 25	-
Toppings and housekeeping pads	20	45	-

SUMMARY

This paper 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. With the exception of concrete flatwork, 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%).

Recent laboratory research and field testing in Canada has indicated that the performance of fly ash concrete, even at relatively high replacement levels, is not adversely affected when portland-limestone cement (PLC) containing up to 15% interground limestone is used in place of portland cement, which typically contains only 3.5% limestone [Thomas et al. 2010]. The use of PLC thus permits a further 10% reduction in the CO_2 footprint of the concrete, in addition to that achieved by using fly ash at the optimum replacement level.

REFERENCES

ACAA, (2006). “2005 Coal Combustion Product (CCP) Production and Use Survey”. *American Coal Ash Association*, http://www.acaa-usa.org

Anon, (1914). "An investigation of the pozzolanic nature of coal ashes." *Engineering News*, Vol. 71, No. 24, pp 1334-1335.

Bamforth, P.B. (1980). “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, pp. 777-800.

Busby and Associates, 2002. “Use of EcoSmart Concrete in the Bayview High-Rise Apartment, Vancouver, B.C.” Report by *Busby and Associates Architects*, http://www.ecosmartconcrete.com

Davis, R.E., Carlson, R.W., Kelly, J.W. and Davis, H.E. (1937). “Properties of cements and concretes containing fly ash.” *Journal of the American Concrete Institute*, Vol. 33, pp. 577-611.

Marceau, M.L., Gajda, J., and VanGeem, M.G. (2002). “Use of Fly Ash in Concrete: Normal and High Volume Ranges,” *PCA R&D Serial No. 2604*, Portland Cement Association, Skokie, Illinois, 2002.

Obla, K.H, Hill, R.L. and Martin, R.S. 2003. “HVFA Concrete – an industry perspective.” Concrete International, August, pp. 29-33.

Thomas, M.D.A. (1997). “Laboratory and field studies of salt scaling in fly ash concrete.” *Frost Resistance of Concrete* (Ed. M.J. Setzer and R. Auberg), Essen, Germany, September

Thomas, M.D.A. (2007). Optimizing the Use of Fly Ash in Concrete. *PCA Report IS548*, Portland Cement Association, Skokie, Illinois, 24p.

Thomas, M.D.A., Hooton, R.D., Cail, K., Smith, B., de Wal, J. And Kazanis, K. (2010). “Use of concrete containing portland-limestone cement and supplementary cementing materials in an aggressive environment.” *Concrete International*, January, pp. 35-41.

USBR, (1948). “Physical and Chemical Properties of Fly Ash - Hungry Horse Dam”. Laboratory Report CH-95, U.S. Bureau of Reclamation.