

MATERIALS TECHNOLOGY LABORATORY

Use of Fly Ash and Slag in Concrete: A Best Practice Guide

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Executive Summary

With the Canadian government's commitment to the Kyoto Protocol, there is an urgent need to improve our greenhouse gas (GHG) emission reduction capabilities in all industrial sectors, including building construction. "Green" concrete using industrial by-products, and environmentally friendly materials and technologies can be considered one of the construction industry's major contributions to Canada's GHG emission reduction efforts.

Cement is the third most energy-intensive material to produce, behind steel and aluminum. The production of every tonne of portland cement contributes about one tonne of carbon dioxide (CO₂) into the atmosphere due mainly to the reduction of limestone to lime and carbon dioxide and to the use of energy in electricity, process heat and transport. Use of reclaimed and recyclable industrial by-products, such as supplementary cementing materials (SCMs) to partially replace portland cement in concrete, reduces GHG emissions and results in sustainable "green" concrete. Additional benefits include minimization of waste disposal for these industrial by-products and lessened pressure on natural resources (such as limestone and iron ore). Importantly, concrete using SCMs will generally exhibit an extended service life over conventional concrete.

The construction industry has been using SCMs such as fly ash and slag in concrete construction for many decades. However, since there is a non-uniform distribution of available supplementary cementing materials, the practice may not be universal from one region to another or from one ready-mixed concrete plant to another. In order to promote the wider use of SCMs in concrete and to enhance consistent application and performance of the technology such that an increase in GHG emission reduction can be achieved, this Best Practice Guide on the use of SCMs in concrete construction has been developed. The objective of this document is to provide basic knowledge in the use of SCMs in concrete, and the impact of SCM use on construction. The Best Practice Guide is the result of the collaborative effort between designers, specifiers, contractors, manufacturers, academicians and users. It is expected that the Best Practice Guide will lead to wider use and acceptance of "green" concrete using SCMs.

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Table of Contents

| | |
|--|-----------|
| Executive Summary | i |
| Acknowledgements..... | ii |
| 1. INTRODUCTION..... | 1 |
| 2. MATERIALS..... | 5 |
| 2.1 Supplementary Cementing Materials (SCMs) | 5 |
| 2.1.1 Fly ash..... | 5 |
| 2.1.2 Ground, granulated blast-furnace slag (GGBFS)..... | 7 |
| 2.2 Cements | 8 |
| 2.2.1 Portland cements..... | 8 |
| 2.2.2 Blended hydraulic cements..... | 8 |
| 2.3 Aggregates..... | 8 |
| 2.4 Chemical admixtures..... | 8 |
| 2.4.1 Air-entraining agents | 9 |
| 2.4.2 Water reducers and superplasticizers (High-Range Water Reducers) | 9 |
| 2.4.3 Accelerators..... | 9 |
| 3. CONCRETE DESIGN CONSIDERATIONS - .. Effect of SCMs on Concrete Properties | 11 |
| 3.1 Fly ash | 11 |
| 3.1.1 Properties of fresh concrete | 11 |
| 3.1.2 Mechanical properties..... | 12 |
| 3.1.3 Durability characteristics..... | 13 |
| 3.2 GGBFS (Slag) | 15 |
| 3.2.1 Properties of fresh concrete | 15 |
| 3.2.2 Mechanical properties..... | 15 |
| 3.2.3 Durability characteristics..... | 16 |
| 4. CONCRETE MIXTURE PROPORTIONS..... | 19 |
| 4.1 Simple replacement method | 19 |
| 4.2 Modified replacement method..... | 19 |
| 4.2.1 Estimation of mixing water..... | 19 |
| 4.2.2 Selection of W/CM..... | 20 |
| 4.3 Fly ash and GGBFS contents | 21 |
| 4.3.1 All types of concrete applications | 22 |
| 4.3.2 Massive concrete structures, for which consideration is given to temperature rise caused by hydration of portland cement | 22 |
| 4.3.3 Concrete exposed to a sulphate environment..... | 23 |
| 4.3.4 Concrete made with reactive aggregates | 23 |
| 4.3.5 Structurally reinforced concrete exposed to chlorides with or without freezing and thawing cycling..... | 24 |

4.3.6 Hand finishing concrete flatwork exposed to a combination of deicing salts and freezing and thawing cycles24

4.4 Examples of projects using fly ash and slag in concrete25

5. PRODUCTION AND PLACING OF CONCRETE27

5.1 Production27

5.2 Placing, finishing and stripping of concrete27

5.2.1 Placing.....27

5.2.2 Finishing.....28

5.2.3 Stripping.....29

6. CURING.....31

6.1 Definition.....31

6.2 Curing objectives.....31

6.3 Curing regimes31

7. QUALITY CONTROL OF CONCRETE INCORPORATING SCMs.....33

7.1 How QC is defined by CSA Standards33

7.2 Quality control of concrete incorporating less than 30% fly ash or 35% slag33

7.3 Quality control of concrete incorporating more than 30% fly ash or 35% slag33

7.4 QC recommendations for concrete incorporating SCMs33

7.4.1 On the SCM itself34

7.4.2 Review of the proposed mixture proportions34

7.4.3 QC by the ready-mixed producer34

7.4.4 QC by the contractor.....34

8. CONCLUSIONS AND RECOMMENDATIONS37

REFERENCES39

1. INTRODUCTION

Sustainable development is a priority for the federal government. Sustainable development in this context means ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’.

In support of the government’s commitment to the Kyoto Protocol and sustainable development initiatives, the construction industry has been developing and using less energy-intensive and more environmentally friendly materials and technologies in concrete construction. “Green” concrete using supplementary cementing materials (SCMs) such as fly ash and slag is one good example.

The production of every tonne of portland cement, an essential constituent of concrete, releases about one tonne of carbon dioxide (CO₂) into the atmosphere. Partial replacement of cement with SCMs reduces greenhouse gas (GHG) emissions proportionately and results in a more “green” concrete, through reduced energy consumption (energy required to produce cement) and avoidance of process emissions (limestone calcination). Additional benefits include minimization of waste disposal (landfilling these industrial by-products), lessened pressure on natural resources (such as reduction in limestone consumption used for the production of cement) and, when SCMs are used judiciously, improved concrete properties and durability.

Use of SCMs in concrete is not new in Canada (1). In Atlantic Canada, with the exception of Newfoundland, almost all concrete contains anywhere from 10 to 25% fly ash. In Ontario, the Ready-Mixed Concrete Association of Ontario estimates that about 60% of the contractors use SCMs in the production of ready-mixed concrete, most of which is ground granulated blast furnace slag (GGBFS). In the Prairies and Western Canada, 80 to 90% of the concrete produced contains fly ash. In Quebec, around 5% of the cement produced is blended cement that contains silica fume, or silica fume with either fly ash or slag.

Many high profile concrete structures such as the Hibernia concrete platform and the Confederation bridge, and high rise buildings such as the Scotia Plaza in Toronto and the Bankers Hall 2 in Calgary were made with SCMs to provide concrete technical benefits and longer service life. EcoSmart Foundation Inc., with support of the Minerals and Metals Program of *Action Plan on Climate Change* (AP 2000), is working to maximize the use of SCMs in concrete and has participated in many concrete projects using high volumes of fly ash. However, despite these efforts, an average of only 10% of the quantity of SCMs produced in Canada is currently used in the cement and concrete industries (1). It is the view of the authors that this quantity can significantly be increased without compromising the performance, constructability, and the cost of concrete structures.

ICON/CANMET recently conducted an extensive investigation into the “Current Situation of SCMs in Canada” (1). The study was commissioned by the Supplementary Cementing Materials components of AP 2000. The study recommended that national guidelines and specifications be developed for the wider use and acceptance of SCMs in construction by specifying authorities, concrete suppliers, users and engineering inspection/testing

organizations. In fact, it is mentioned in the above study that some specifiers in certain engineering firms or municipal, provincial, and federal authorities place restrictions on the use of SCMs in concrete based on perception, lack of technical information or knowledge of the properties of SCMs, or on bad experiences due, so often, to a lack of knowledge. Such restrictions could actually be detrimental to the long-term durability of concrete for reasons of ASR mitigation (alkali-silica reaction) among others.

With the support from AP 2000, CANMET and Public Works & Government Services Canada (PWGSC), this comprehensive technical Best Practice Guide has been developed to assist mainly specifiers, manufacturers and users in the use of SCMs in concrete. The goal of developing this Best Practice Guide is to advance the greening of concrete construction through the use of technically, financially, environmentally and socially acceptable technologies.

The main SCMs addressed in this Best Practice Guide are fly ash and ground granulated blast furnace slag, which are considered the SCMs most readily available and widely used in concrete in Canada. Silica fume is mainly used for improving specific properties of the concrete, and has a less significant impact than other SCMs in terms of reducing greenhouse gas emissions associated with the production of concrete (since the replacement of cement by silica fume in common construction practice is relatively small). Natural pozzolans such as diatomaceous earth, metakaolin and volcanic ashes, due to their unique nature and current limited utilization in Canada, will not be discussed in this Best Practice Guide.

This Best Practice Guide document is divided into eight sections:

1. Introduction.
2. Typical characteristics of materials used in concrete construction (SCMs, cement, aggregates, and chemical admixtures) with reference to appropriate standards that govern their production, evaluation and use.
3. Effect of SCMs on the properties of fresh and hardened concrete, which should help specifiers, designers and structural engineers evaluate the suitability of SCMs for use in concrete for different applications.
4. Effect of SCMs on concrete mixture proportioning, and provides guidance to contractors and specifiers on SCMs contents for use in specific projects.
5. Impact of SCMs on concrete production, placing, and finishing.
6. Importance of curing for concrete incorporating SCMs as compared to conventional concretes.
7. Quality control requirements for concrete construction using SCMs.
8. Conclusions and recommendations.

In this Best Practice Guide, the term “portland cement concrete” is used to describe concrete made with portland cement as the *only* cementitious material. In concrete using SCMs, the cementitious materials would include portland cement as well as SCMs. Also, the term “slag” is sometimes used to describe Ground Granulated Blast Furnace Slag (GGBFS). The SCMs percentages reported in the Best Practice Guide are based on the total weight of cementitious materials.

2. MATERIALS

This section summarizes the typical characteristics of the materials for use in concrete (SCMs, cement, aggregates, chemical admixtures) with reference to the appropriate standards that govern their production, evaluation (Quality Control) and use. Emphasis is given to SCMs.

2.1 Supplementary Cementing Materials (SCMs)

Supplementary cementing materials are materials that when used with portland cement contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity or both. Typical examples are fly ash, ground granulated blast furnace slag (GGBFS), silica fume and natural pozzolans. This document discusses fly ash and slag only.

2.1.1 Fly ash

Definition and types

Fly ash is the finely divided residue that results from the combustion of pulverized coal that is carried from the combustion chamber of a furnace by exhaust gases. Specifications for the use of fly ash in concrete are given in CSA A3001, which classifies fly ash as F, CI, or CH by its calcium oxide content. Type F refers to fly ash with CaO content less than 8%, Type CI has a CaO content ranging from 8 to 20%, and Type CH fly ash has a CaO content greater than 20%. Higher CaO content generally denotes higher self-cementing properties. In Canada, two Types of fly ash are produced and used: Type F and Type CI. However, Type CH fly ash has been imported from the U.S.A. and used in concrete in Canada.

Production and availability

The production of fly ash in Canada accounts for 4.8 Mt/y; about 60% is produced in Alberta, and the balance is produced in five other provinces i.e., Saskatchewan, Manitoba, Ontario, New Brunswick, and Nova Scotia. About 10% of the fly ash produced in Canada is used in the cement and the concrete industry. Currently, most of the fly ash potentially useable as SCMs in concrete is produced in Saskatchewan and Alberta.

In the last few years, power companies in Atlantic Canada have been blending petroleum coke with coal to fire the furnaces in thermal generating stations. This practice generally renders the as-produced fly ash unsuitable for use in concrete due to unacceptably high levels of unburned carbon in the ash. However, there are technologies available for removing the carbon, and it is envisaged that fly ash suitable for use as a SCM will be produced in the Atlantic provinces in the near future. Currently, the fly ash that is used in this region is imported from the U.S.A. Some of the fly ash used in Quebec, Ontario and British Columbia is also imported from the U.S.A.

Chemical composition requirements

The current CSA A 3000-03 standard permits a maximum of 5% SO₃ content for Type F fly ash and a maximum loss on ignition (LOI) of 8%. The maximum SO₃ and LOI contents for both Types CI and CH is 5% and 6%, respectively.

The SO₃ content has been reported to influence to some degree the early-age compressive strength of mortar and concrete specimens. The higher SO₃ content, the higher is the resultant early age strength. However, a maximum limit on SO₃ is considered necessary in order to avoid an excess sulphate content in hardened concrete, which may contribute to disruptive expansion due to internal sulphate attack.

The LOI is determined by the mass loss of fly ashes heated at a temperature of 750 ± 25°C; unburned carbon is the largest component of LOI. The water required for workability of concretes is influenced by the carbon content of fly ashes, and the shape of carbon particles (porosity): the higher the carbon content of a fly ash, the more water is needed to produce a paste of normal consistency. Also, the dosage of air entraining admixtures for fly ash concrete, to achieve a certain air content, increases with an increasing carbon content in the fly ash used (carbon absorbs organic admixtures such as air entraining agents). The water demand and the dosage of air-entraining admixtures both increase with increasing porosity of the carbon particles.

Physical properties and requirements

The physical properties of fly ash vary over a wide range. The specific gravity (SG), for instance, ranges from a low value of ~1.90 in some fly ashes to a high value of ~3.00 for iron-rich fly ash. SG values of around 2.2 are, however, common. By comparison, the specific gravity of portland cement is ~3.15.

Fineness is one of the primary physical characteristics of fly ash that relates to its pozzolanic activity. It is well known that particles larger than 45µm show little or no reactivity under normal hydration conditions. It has been reported that the pozzolanic activity is directly proportional to the amount of particles finer than 10µm (2). The fineness of fly ash ranges from less than 2% retained to more than 30% retained on the 45µm sieve. CSA A 3001 limits the maximum value at 34% for the amount of material retained on a 45µm sieve.

In the CSA A 3000-03 standard, the autoclave expansion test is employed to ensure proper soundness and avoid disruptive expansion of concrete caused by magnesia (MgO) and free lime (CaO) in cement/fly ash. CSA states that the maximum permissible expansion must be less than 0.8% in the autoclave test. The presence of MgO in a form capable of hydrating to form magnesium hydroxide (brucite) in the hardened concrete is suspected to cause this expansion. However, deleterious expansion due to this reaction has never been identified in practice.

Mineralogical composition

Mineralogical analysis of fly ashes typically shows 50-90% of noncrystalline particles, or glass, and some crystalline phases. The reactivity of fly ashes is predominately related to the noncrystalline phase, or glass. Higher calcium fly ashes (e.g. Type CH) contain significant quantities of reactive crystalline phases that influence the properties of the fly ash in concrete.

Quality control

The fly ash from a given power plant may vary with time depending on many factors such as changes in the burning conditions, or source and composition of coal. Variations in the fly ash

properties may affect the performance of the concrete. The fly ash properties that are most likely to affect its performance in concrete are fineness, particle shape, glass content and composition, LOI, autoclave expansion, SO₃, CaO, and alkali contents. Variability of fly ash colour should also be monitored for architectural concrete applications. Changes in fly ash colour can also indicate changes in carbon content or power-plant burning conditions, which could affect the performance of fly ash in air-entrained concrete.

2.1.2 Ground, granulated blast-furnace slag (GGBFS)

Definition

Ground, granulated blast-furnace slag (GGBFS) is a nonmetallic product consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace, then water chilled rapidly to form glassy granular particles, and then ground to cement fineness or finer. In concrete, GGBFS reacts with portland cement to form cementitious products. Slag possesses both cementing and pozzolanic properties. The physical and chemical requirements of GGBFS for use in concrete are given in CSA A 3000-04.

Production and availability

The total Canadian GGBFS production is concentrated in Ontario, related to iron production by Dofasco and Stelco in Hamilton and Nanticoke as well as Algoma Steel in Sault Ste. Marie. Slag has been extensively used by the Ontario cement and the concrete industry since the early 1980s. About 1.44 Mt/y of blast furnace slag (BFS) is produced in Ontario, but only about 380 kt/y is produced as GGBFS. Most of GGBFS is used in the cement and concrete industry in Ontario. The production of GGBFS in Canada could, however, increase if the demand increases. In fact, Stelco in Nanticoke has recently started producing about 100 kt/y of GGBFS, increasing the total production of GGBFS in Canada to ~480 kt/y.

Chemical composition requirements

Compared to fly ash, GGBFS is usually rich in calcium and magnesium oxides. For similar reasons as mentioned above for fly ash, CSA A3000-04 limits the SO₃ and sulphide sulphur contents in GGBFS to 4.0, and 2.5%, respectively.

Physical properties and requirements

Unlike fly ash, GGBFS is ground to a desired particle size or surface area, depending on the degree of activation needed and economic considerations. It is reported that slag particles < 10 µm contribute to early strength development (up to 28-day); particles in the 10-45 µm range continue to hydrate beyond 28 days and contribute to later-age strength; and particles above 45 µm generally show little or no activity. CSA limits the proportion of particles >45 µm to 20%.

Typically, in order to obtain satisfactory strength development in concrete, the Blaine surface area of GGBFS ranges between 4000 and 6000 cm²/g. For example, the Canadian GGBFS from Sault St. Marie is typically ground to Blaine fineness of 4500 cm²/g.

In order to avoid disruptive expansion of concrete containing GGBFS, due to the MgO content, CSA A3000-03 limits the maximum autoclave expansion to 0.8%.

Mineralogical composition

Mineralogical analyses of GGBFS samples show glass contents ranging from 80 to 100%. As with fly ash, the reactivity of GGBFS is strongly dependent on the glass content.

2.2 Cements

2.2.1 Portland cements

Types of portland cement and blended hydraulic cements as defined by CSA A3000-03 are given in Table 2.1. There is no restriction on the type of portland cement that can be used with fly ash and GGBFS to produce concrete. Portland cement must meet the CSA A3000-03 requirements. However, when high-early strength is required, the use of CSA Type HE cement is an option. Low/moderate heat or low/moderate sulfate resistance properties can be conferred on concrete by using, respectively, Type MH/LH or MS/LS portland cements. This can also be achieved by using Type GU cement with an appropriate amount of fly ash or slag added at the ready-mixed concrete batch plant.

Table 2.1 Portland cements and blended hydraulic cements as defined by CSA A3000-03

| Portland cement type | Blended hydraulic cement type | Name |
|----------------------|-------------------------------|------------------------------------|
| GU | GUb | General use cement |
| MS | MSb | Moderate sulphate-resistant cement |
| MH | MHb | Moderate heat of hydration cement |
| HE | HEb | High early-strength cement |
| LH | LHb | Low heat of hydration cement |
| HS | HSb | High sulphate-resistant cement |

2.2.2 Blended hydraulic cements

Blended hydraulic cements as defined by CSA A3000-03, can include various proportions of one (binary), two (ternary) or three (quaternary) SCMs such as fly ash, GGBFS and silica fume. These cements can be used with additional fly ash and slag added at the concrete batch plant.

2.3 Aggregates

Fine and coarse aggregates should meet the requirements of CSA A23.1. There are many reports indicating that alkali-aggregate reactions can be mitigated by the proper use of fly ash or GGBFS. The proper amount of these SCMs to control alkali-aggregate reactions in concrete will depend on the reactivity of the aggregate and should be determined through a testing program as detailed in CSA A23.2-28A or by following the standard practice in CSA A23.2-27A.

2.4 Chemical admixtures

The chemical admixtures used in concrete incorporating SCMs should conform to the requirements of ASTM C 260, C 494, and C 1017. In determining the quantities of admixtures to use, the SCM is usually added to the mass of cement.

2.4.1 Air-entraining agents

In general, the dosage of air-entraining admixtures required for a concrete to achieve a certain air content increases with an increasing fly ash content, and increasing fineness and loss on ignition value of a fly ash. It also marginally increases in some cases with increasing slag content and fineness.

2.4.2 Water reducers and superplasticizers (High-Range Water Reducers)

In general, fly ash increases the workability of a given mix and the water content can be reduced to achieve a given workability. For GGBFS, the water reduction depends strongly on the fineness.

No compatibility issues have been found between the Canadian fly ashes/slag and the commonly used types of superplasticizers in Canada. However, compatibility tests are recommended, especially for SCMs concrete with a low water-to-cementitious materials ratio (W/CM), typically lower than 0.35.

2.4.3 Accelerators

The use of low-calcium fly ash and, to some extent, high calcium fly ash and GGBFS, generally decrease the early-age strength of concrete, especially in cold weather, compared to a normal portland cement concrete with similar workability and similar 28-day compressive strength. Accelerators can be used to partially compensate for this early-age strength reduction. However, calcium chloride is not recommended as an accelerator for concrete with high volumes of fly ash or for any reinforced or pre-stressed concrete.

3. CONCRETE DESIGN CONSIDERATIONS - Effect of SCMs on Concrete Properties

The following provides a summary of the effect of fly ash and GGBFS on the main properties of concrete. These are general statements based on a review of scientific literature that generally compares concrete incorporating SCMs to a portland cement concrete with similar workability and similar 28-day compressive strength. However, each material from each specific source possesses its own characteristics, and the extent to which a given material influences the properties of concrete will depend on those specific characteristics and should be determined by trial mixtures prior to use.

3.1 Fly ash

The properties of the fresh concrete, as well as its mechanical properties and durability will be influenced by the incorporation of fly ash as a replacement for portland cement. The extent to which these properties will be affected will depend on the nature and proportion of fly ash used. The following outlines the manner in which fly ash will affect the properties of concrete, in general.

3.1.1 Properties of fresh concrete

Slump and workability

It is generally known that the partial replacement of portland cement by fly ash in concrete reduces the water requirement to obtain a given consistency, or increases the workability and slump for a given water content compared to that of concrete without fly ash. This phenomenon is generally attributed to the spherical shape and smooth surface of fly ash particles as opposed to angular cement particles. Particularly in the manufacture of precast concrete, the workability improvement can result in elements with sharp and distinctive corners and edges and with a better surface appearance.

Bleeding

The bleeding of fly ash concrete depends on the manner in which the fly ash is used. When fly ash is used as a direct replacement for cement with no reduction in water content, the bleed water of the fly ash concrete generally increases. However, when a reduction of water due to the use of fly ash as a replacement of cement in concrete is made to maintain similar workability, the bleed water of the resulting fly ash concrete is generally lower than that of concrete made without fly ash.

High-volume fly ash concrete at low unit water content does not bleed. This generally creates a problem for finishers of flatwork surfaces who are used to more bleed water at the surface during finishing. As with any concrete, particularly with a low water-to-cementitious material ratio, care is required to prevent plastic shrinkage cracking at the surface immediately after placing by following the measures proposed by ACI 305 committee on hot weather concreting. Plastic cracking occurs when the rate of evaporation at the concrete surface exceeds the rate at which bleed water replenishes water at the surface.

Autogenous temperature rise

The use of low-calcium fly ash as partial replacement of portland cement in concrete will generally contribute to reducing the temperature rise in concrete compared to portland cement concrete. This is important in mass concrete to reduce the potential for cracking associated with excessive thermal gradients. High-calcium fly ashes, depending on the total alkali content may increase the temperature rise. In general, if a Type CH fly ash is to be used as a potential means to reduce temperature in concrete, concrete mixtures should be evaluated for this particular property.

Setting time

For similar 28-day compressive strength and workability, the setting time of fly ash concrete may be longer than normal portland cement concrete for a given combination of cement and chemical admixtures (especially for Type F fly ash). This may influence the schedule for finishing horizontal surfaces, especially at high levels of replacement (>~30%), and/or in cool weather. In this case, using a dosage of water reducer in the lower limit of the range proposed by the manufacturer can contribute to decreasing, to some extent, the initial setting time of fly ash concrete. However, this should not be at the expense of strength development and durability of the concrete. Still, in hot weather conditions, extended setting time can be beneficial.

Concrete accelerators may be used to offset increase in setting time when using fly ash.

3.1.2 Mechanical properties

Strength development

The strength development of fly ash concrete is strongly affected by the type of fly ash and the curing temperature. The use of low-calcium fly ashes (CSA Type F and CI) generally decreases the compressive strength of concrete at early ages (up to 28 days) and increases it at later ages (due to the pozzolanic reaction of fly ash) when compared to portland cement concrete with similar 28-day compressive strength. On the other hand, the use of high-calcium content (CSA Type CH) has a marginal effect on strength development.

In cool weather, the low temperature generally slows down the chemical reaction between cement and water, and thus the strength development of concrete. For fly ash concrete, this effect is more pronounced due to reduced portland cement in the mixture and greater dependence of the pozzolanic reaction on temperature.

However, concrete with fly ash can be proportioned to achieve similar 1-day strength as a portland cement concrete mixture by judicious proportioning of the mixture. This usually requires a reduction in water-to-cementitious materials ratio (W/CM), the reduction being greater with higher levels of SCMs (and particularly for Type F ashes, a somewhat higher total cementitious materials content). It should be noted that the reduction in strength might not be as pronounced in precast concrete where heat curing is used. The reduction in early age strength can also be partially compensated for by incorporating silica fume with fly ash to produce a ternary blended cement or by using suitable accelerators.

As an example, published data on the York University project have shown that with proper mix design it is possible to achieve one-day compressive strength of about 16 MPa with concrete incorporating 50% Type CI fly ash (3).

Young's modulus of elasticity

Since the modulus of elasticity of concrete is related to its compressive strength, in general, the effect of fly ash on the elastic modulus of concrete is similar to the effect of fly ash on strength development. Therefore, the elastic modulus of fly ash concrete is generally lower at early ages and higher at later ages than that of concrete made without fly ash, and having similar 28-day compressive strength.

Drying shrinkage

The effect of fly ash on drying shrinkage is highly dependent on how the concrete is proportioned. If full advantage is taken of the reduced water demand and the unit water content is reduced and if the W/CM is also reduced to achieve strength parity at 28 days, fly ash concrete will have significantly reduced shrinkage compared to portland cement concrete. The impact of fly ash on drying shrinkage also depends on the maturity of the concrete when drying commences. If drying starts at one day, fly ash concrete may shrink more. Hence the importance of proper curing of fly ash concretes.

Creep

The effect of fly ash on creep is mainly related to the effect that fly ash has on the ultimate strength of concrete. Since fly ash increases the ultimate strength of concrete due to the pozzolanic reaction, the creep of fly ash concrete is generally lower than that of a portland cement concrete with similar 28-day compressive strength. However, if the fly ash concrete is loaded at an early age, the creep may be higher.

3.1.3 Durability characteristics

Corrosion resistance

The incorporation of fly ash in concrete results in finer pores in the hydrated cement paste leading to a decrease in permeability and chloride ingress rates. Properly proportioned fly ash concrete subjected to adequate curing should, in general, be less permeable at later ages than a corresponding portland cement concrete (having similar 28-d strength), and thus provide better corrosion protection for the reinforcing steel (4). Fly ashes will generally increase chloride binding, further improving resistance to chloride penetration (5).

Resistance to freezing and thawing

The resistance to freezing and thawing cycling of concrete is not affected by the use of fly ash. This property is a direct function of the air-void spacing factor of concrete that is obtained by the proper use of air-entraining admixtures. However, fly ash concrete must have adequate strength prior to exposure to freezing as is the case for normal portland cement concrete.

Resistance to de-icing salt scaling

Laboratory test data (6,7) indicate that fly ash concrete containing more than about 25 % fly ash is less resistant to deicing salt scaling than portland cement concrete. However, some field data have shown acceptable performance of concrete incorporating more than 40 to 50% of fly

ash (and that type CH ash performs generally better than Type F ash) (8). This is partially due to the severity of the ASTM laboratory test, as has been reported in several published technical papers (8, 9, 10). A recent study has shown that the BNQ procedure (standard test of the province of Quebec, Canada) simulates better the scaling resistance of the concrete incorporating SCMs compared to ASTM procedure (10). Nonetheless, the percentage of fly ash that can be recommended for use in concrete flatwork exposed to deicing salts is still limited to maximum 25 to 35% until salt scaling in concrete containing fly ash is better understood.

Sulphate resistance

In general, low calcium fly ashes (CSA Type F ash) have been found to increase the sulphate resistance of concrete. However, this may or may not be so with high calcium fly ashes. There are data that indicate that poor sulfate resistance is usually confined to fly ashes with more than 20% CaO i.e. Type CH (rarely used in Canada) and that Type F and CI fly ashes can produce equivalent performance to a HS or MS cement when used with a high-C₃A Type GU cement at replacement levels of about 20% (11).

Alkali silica reactions (ASR)

In general, the use of fly ash can mitigate the expansion caused by alkali-silica reactions in concrete. However, the amount of fly ash to be used for controlling alkali-silica reactions depends on the type of reactive aggregate, the exposure conditions, the alkali content of the concrete, the type of fly ash and the water-to-cementing materials ratio of the mixture. Published data indicate that the percent replacement of cement by low-calcium fly ash (CSA Type F and CI fly ashes) required to mitigate ASR may range from 25 to 35% (12). For high-calcium fly ashes (CSA Type CH fly ashes), there is some indication that effective replacement levels may be much higher than those for low-calcium ashes. The exact amounts required have to be determined following the approach described in CSA A23.2-28A.

Carbonation

The use of fly ash decreases the permeability of concrete and thus inhibits the easy penetration of carbon dioxide into the concrete. However, it also reduces the calcium hydroxide content in concrete due to the pozzolanic reaction, and consequently shows an increased propensity for carbonation. Also, fly ash concrete usually takes longer to reach the same level of strength as concrete made without fly ash. Therefore, a fly ash concrete not properly cured may carbonate more than portland cement concrete, especially at higher replacement levels. When carbonation is likely to be an issue, concrete with high levels of SCM requires extended curing and/or reductions in W/CM (13).

Durability in marine environment

Permeability is considered the major factor affecting the durability of concrete in seawater. Therefore, it is evident that fly ash has the potential to improve concrete durability in a marine environment provided it is well cured. In a study conducted by CANMET on fly ash concrete prisms exposed to the marine environment at Treat Island, Maine, US since 1987, the results have shown that concrete with 25% cement replacement with fly ash can be satisfactory under such severe conditions of exposure, provided the W/CM is less than 0.50. For concrete incorporating 55% Type F fly ash, the W/CM should not exceed 0.32 (14).

3.2 GGBFS (Slag)

The properties of the fresh concrete, as well as its mechanical properties and durability will be influenced by the incorporation of slag as a replacement for portland cement. The extent to which these properties will be affected depends on the percentage of slag used and its fineness. The following outlines the manner in which the replacement of portland cement by slag affects the properties of concrete. For more details, the reader could refer to the paper by R.D. Hooton (16).

3.2.1 Properties of fresh concrete

Slump and workability

GGBFS improves the workability and cohesiveness of concrete, but greater improvement is obtained with higher GGBFS contents. High fineness GGBFS does not improve the workability of concrete.

Bleeding

The use of slag does not have a significant influence on bleeding of concrete.

Autogenous temperature rise

The use of slag may reduce the autogenous temperature rise in concrete elements and the associated risk of thermal stress and cracking if sufficiently large percentages of slag are used as a partial replacement for portland cement (i.e. at least 50%, and provided the slag is not ground to a very high fineness: $> \sim 6000$ Blaine). Higher levels of replacement ($> 65\%$) may be needed in warm weather.

Setting time

The setting time of slag concrete may be longer compared to portland cement concrete especially in cold weather. The slower set will depend on the reactivity of the slag and the percentage of slag used. This may influence the schedule for finishing flatwork surfaces (especially for higher volume replacements such as 40% or higher).

Due to its slightly slower strength development, slag concrete is more sensitive than conventional concrete to cold weather conditions for concrete placing. This may further slow the setting time of slag concrete. In warm weather, setting times are similar to those of portland cement concrete.

3.2.2 Mechanical properties

Strength development

In general, concrete containing GGBFS gains strength more slowly, tending to have lower strength at early ages, and equal or higher strength at later ages compared to that of portland cement concrete of similar 28-day compressive strength. However, at an equivalent replacement level, this effect is less than that for most fly ashes. In hot weather, strength gain can be as high or higher than portland cement concrete.

The slightly slower strength development and resulting lower early-age strengths of slag concrete might be a problem for form removal in some cases when high percentages of slag are used, especially in cold weather conditions. As for fly ash, this can be overcome by a judicious

proportioning of the concrete mixture such as reducing the W/CM or adding silica fume to produce a ternary blend.

Drying shrinkage

There is no significant difference in the shrinkage characteristics of concrete with and without GGBFS as part of the cementitious materials if the paste content is the same. Also, advantage may be taken of the improved workability and associated water reduction achievable with GGBFS.

Creep

GGBFS appears to reduce creep due to the increase of the ultimate strength and elastic modulus of concrete with GGBFS. However, if the concrete is loaded at early ages, the creep might be higher than that of portland cement concrete, due to the lower early age strength of concrete with GGBFS.

3.2.3 Durability characteristics

Corrosion resistance

The incorporation of GGBFS in concrete increases its resistance to chloride-ion penetration, especially at later ages. It also improves chloride binding. This is very advantageous for protecting reinforcing steel from corrosion. This assumes that the slag concrete is well cured as mentioned for fly ash concrete.

Resistance to freezing and thawing

The resistance to freezing and thawing cycling of concrete is not affected by the use of GGBFS. This property is a direct function of the air-void spacing factor of concrete that is obtained by the proper use of air-entraining admixtures. However, concrete must have adequate strength prior to exposure to freezing, as it is the case for normal portland cement concrete.

Resistance to de-icing salt scaling

As for fly ash concrete, laboratory data indicate that slag concrete is slightly less resistant to deicing salt scaling than portland cement concrete (9). This limits the percentage of slag that can be recommended in concrete flatwork exposed to deicing salts to less than 50% although there are some contradictory results on this issue.

Sulphate resistance

Concrete containing GGBFS dosages greater than 35% by mass of cementitious material, has demonstrated an improvement in resistance to sulphate attack. For equivalent performance to Type HS cement, slag levels of 35 to 65% may be required depending on the Al_2O_3 content of the slag. Increasing slag levels would be required with increasing Al_2O_3 content in the slag.

Resistance to alkali silica reaction

The incorporation of slag in adequate percentages (usually more than 35%) can be used to mitigate the expansion caused by alkali-silica reaction in concrete. Specific guidance is provided in CSA A 23.2-27A.

Carbonation

As for fly ash concrete, concrete with GGBFS if not properly cured may carbonate more than portland cement concrete.

Durability in marine environments

Permeability is considered the major factor affecting the durability of concrete in seawater. Therefore, it is evident that GGBFS has the potential to improve concrete durability in the marine environment particularly, given slag performance in chloride environments.

Table 3.1 gives a summary of the general effects of fly ash and GGBFS on concrete properties.

Table 3.1 – Summary of General Effects of Fly Ash and GGBFS on Concrete Properties
(Comparison with portland cement concrete with similar 28-day compressive strength)

| | Fly Ash | GGBFS | Comments |
|------------------------------|---------|-------|--|
| Fresh properties | | | |
| Water demand | ↘ | ↘~ | Fly ash: the water reduction decreases with increasing fineness and carbon content of fly ash. GGBFS: does not have a strong effect on water demand. |
| Workability | ↗ | ↗~ | Fly ash: the spherical particle shape of fly ash assists in improving workability. GGBFS: does not have a strong effect on slump, but increases the pumpability. |
| Bleeding | ↘ | ~ | Fly ash: bleeding and segregation are in general reduced and pumpability is improved. However, the low bleed water may increase the risk of plastic shrinkage cracking. GGBFS: does not have a strong effect on bleeding. |
| Setting times | ↗ | ↗ | Fly ash: longer setting times compared to normal concrete which may affect the finishing schedule. Cold weather conditions may further slow setting times. GGBFS: its effect on setting times is less than that of fly ash. |
| Autogenous temperature rise | ↘ | ↘ | Fly ash: generally reduces the risk of thermal stress and cracking (especially type F and CI). GGBFS: may reduce the risk of thermal cracking if at least 50% is used and the Blaine fineness is lower than 6000 cm ² /g, and if at least 65% is used in warm weather. |
| Mechanical properties | | | |
| Compressive strength | ↘ ↗ | ↘ ↗ | Fly ash: Decreases the mechanical properties at early ages (especially at 1-d and in cold weather). The long-term mechanical properties such as compressive and flexural strengths, and the modulus of elasticity of fly ash concrete are typically superior to those of portland cement concrete of similar 28-day compressive strength. GGBFS: similar behavior to fly ash concrete, except that slag concrete has higher early-age mechanical properties and lower long-term mechanical properties compared to fly ash concrete with similar contents. |
| Flexural strength | ↘ ↗ | ↘ ↗ | |
| Modulus of elasticity | ↘ ↗ | ↘ ↗ | |
| Drying shrinkage | ~ ↘ | ~ | |
| Creep | ~ ↘ | ~ ↘ | |
| Durability | | | |
| Permeability | ↘ | ↘ | Fly ash: reduces water and chloride-ion permeability, especially at later ages, if well cured. GGBFS: similar to fly ash |
| Corrosion resistance | ↗ | ↗ | Fly ash: increases the protection of reinforcing steel from corrosion if well cured. GGBFS: similar to fly ash |
| Sulphate resistance | ↗ | ↗ | Fly ash: the use of low calcium fly ash (CSA Class F and CI with CaO content < 20%) increases resistance to sulphate attack. Fly ashes with more than 20% CaO should be investigated for sulphate resistance (rarely used in Canada). GGBFS: the content required should be investigated (usually more than 35% is required) |

| | Fly Ash | GGBFS | Comments |
|----------------------------------|----------------|--------------|---|
| ASR resistance | ↗ | ↗ | Fly ash: the use of 25 to 35% fly ash would normally be effective in controlling ASR expansion with most alkali-silica reactive aggregate if the CaO content of the fly ash used is below ~20% and its alkali equivalent is below 4.5%. For fly ash with higher CaO and alkali contents, the exact amount required should be determined following the approach described in CSA A23.2-28A. GGBFS: the amount required should be determined according to CSA A23.2-27A (usually more than 35%). |
| De-icing salt scaling resistance | ↘ | ↘ | Fly ash: lab data have shown that fly ash (>25%) decreases the scaling resistance of concrete, but this has not been confirmed by field data. GGBFS: same as for fly ash concrete. |
| Carbonation resistance | ↘~ | ↘~ | Lab data have shown that concrete resistance to carbonation decreases with increasing SCM content, unless the curing period is increased and/or the w/cm is reduced |

↘: decreases; ↗: increases; ~: no significant effect

4. CONCRETE MIXTURE PROPORTIONS

The procedure for selection of mixture proportions used for portland cement concrete is also applicable to concrete incorporating fly ash or slag with some modifications (ACI 211.1-91, page 6). The main steps of this procedure are as follows:

- Estimation of mixing water and selection of air content; (compliant with CSA A23.1)
- Selection of water-to-cementitious materials ratio (W/CM) to meet durability and strength parameters;
- Calculation of cement content;
- Calculation of coarse aggregate content;
- Calculation of fine aggregate content;
- Selection of admixture dosage rates;
- Adjustment for aggregate moisture, and;
- Trial batch adjustments.

The above steps may be affected depending on the method used for the incorporation of fly ash/GGBFS in concrete.

4.1 Simple replacement method

This method consists of a direct replacement of a portion of portland cement by fly ash or GGBFS on a one-for-one basis either by volume or by mass, which mainly consists of modifying an existing portland cement mix to include fly ash or GGBFS without other adjustments. The concrete designed with this method usually has lower performance compared to that of concrete made with portland cement only.

4.2 Modified replacement method

This method consists of developing fly ash/GGBFS concrete mixtures with similar workability and similar compressive strength to that of portland cement concrete at a specified age. In general, these concretes have a higher total weight of cementitious materials, and lower W/CM than that of portland cement concrete.

In this recommended method, the first two steps of the above procedure, i.e. the estimation of mixing water and the selection of W/CM, need to be modified.

4.2.1 Estimation of mixing water

As mentioned earlier, the use of fly ash in concrete generally reduces the water demand required to achieve a certain level of workability, while the use of GGBFS does not significantly affect the water demand. Therefore, for each type of fly ash and fly ash content (and the same thing for GGBFS to some extent), data should be developed to replace values usually used in ACI 211.1-6 in the table that provides the approximate mixing water content for different slumps and nominal maximum sizes of aggregates. Mixing water is also dependent on the sand gradation. The unit water content of the concrete mixture designed for

long-term durability should be as low as practical. Consideration should always be given to using water-reducing admixtures.

4.2.2 Selection of W/CM

The selection of W/CM is related to durability requirements and to the specified compressive strength (usually at 28 days). The use of fly ash and GGBFS affects the strength development of concrete, and consequently the relationship between compressive strength and the W/CM. Trial batches can be made in order to develop this relationship. The design of the laboratory program would preferably use a factorial design optimization method that provides, with a minimum of well-planned trial batches, the possibility to explore a large range of compositions. The relationships will also depend on the type of fly ash/GGBFS, the type of cement used, and curing conditions.

In general, to achieve similar early-age strength (up to 28 days) as a portland cement concrete, fly ash and slag concrete might require lower W/CM.

In the new draft of CSA A23.1 that will be available in early 2005, it is mentioned that for concrete in which the fly ash and slag contents satisfy the following equation $FA/40 + S/45 > 1$, the maximum W/CM of the concrete should meet the CSA requirements, except when the concrete is exposed to freezing and thawing in which case the CSA required values should be reduced by 0.05 (Table 4.1). Also, for reinforced concrete elements exposed to moisture and air, with depths of cover less than 50 mm, the W/CM should not be greater than 0.40 for HVSCM1 ($FA/40 + S/45 > 1$) and not greater than 0.45 for HVSCM2 ($FA/30 + S/35 > 1$).

Table 4.1 Maximum W/CM requirements for different CSA Classes of exposure, and different SCMs contents

| Class of exposure * | Not HVSCM (High Volume SCM) concrete | HVSCM2 [†] exposed to freeze-thaw cycles | HVSCM1 [‡] exposed to freeze-thaw cycles |
|---------------------|--------------------------------------|---|---|
| C-XL | 0.37 | 0.37 | 0.32 |
| C-1 | 0.40 | 0.40 | 0.35 |
| C-2 | 0.45 | 0.45 | 0.40 |
| F-1 | 0.50 | 0.50 | 0.45 |
| F-2 | 0.55 | 0.55 | 0.50 |
| A-1 | 0.40 | 0.40 | 0.35 |
| A-2 | 0.45 | 0.45 | 0.40 |
| A-3 | 0.50 | 0.50 | 0.45 |
| S-1 | 0.40 | 0.40 | 0.35 |
| S-2 | 0.45 | 0.45 | 0.40 |
| S-3 | 0.50 | 0.50 | 0.45 |

* Refer to Table 4.2

[†] Concrete with SCMs contents meeting the following equation $FA/30 + S/35 > 1$ (FA: % fly ash, S: %Slag)

[‡] Concrete with SCMs contents meeting the following equation $FA/40 + S/45 > 1$ (FA: % fly ash, S: %Slag)

Table 4.2 Exposure classes as defined by CSA A23.1

| Class of exposure* | Definition |
|---------------------------|--|
| C-XL | Structurally reinforced concrete exposed to chlorides or other severe environments with or without freezing and thawing conditions, with higher durability performance expectations than the C-1, A-1 or S-1 classes. |
| C-1 | Structurally reinforced concrete exposed to chlorides with or without freezing and thawing conditions. |
| C-2 | Non-structurally reinforced (i.e., plain) concrete exposed to chlorides and freezing and thawing. |
| C-3 | Continuously submerged concrete exposed to chlorides but not to freezing and thawing. |
| C-4 | Non-structurally reinforced concrete exposed to chlorides but not to freezing and thawing |
| F-1 | Concrete exposed to freezing and thawing in a saturated condition but not to chlorides. |
| F-2 | Concrete in an unsaturated condition exposed to freezing and thawing but not to chlorides. |
| N | Concrete exposed neither to chlorides nor to freezing and thawing. |
| A-1 | Structurally reinforced concrete exposed to severe manure and/or silage gases – with or without freeze-thaw exposure. Concrete exposed to the vapour above municipal sewage or industrial effluent, where hydrogen sulphide gas may be generated. |
| A-2 | Structurally reinforced concrete exposed to moderate-severe manure and/or silage gases and liquids – with or without freeze-thaw exposure. |
| A-3 | Structurally reinforced concrete exposed to moderate-severe manure and/or silage gases and liquids – with or without freeze-thaw exposure in a continuously submerged condition. Concrete continuously submerged in municipal or industrial effluents. |
| A-4 | Non-structurally reinforced concrete exposed to moderate manure and/or silage gases and liquids – without freeze-thaw exposure. |
| S-1 | Concrete subjected to very severe sulphate exposure. |
| S-2 | Concrete subjected to severe sulphate exposure. |
| S-3 | Concrete subjected to moderate sulphate exposure. |

4.3 Fly ash and GGBFS contents

The following paragraphs present recommended percentages of fly ash and slag to be used in concrete for different applications whenever it is technically and economically feasible. Summary of the recommended percentages is given in Table 4.3. Specific percentages need to be determined for each specific project depending on the following factors:

- The properties of the fly ash and slag, i.e. its reactivity, its influence on water demand in concrete, its influence on the dosage of admixtures, and the variability of the material.
- The required service life of the structure, and the type of exposure to which the concrete is subjected.
- The curing temperature (cool vs. hot weather).

- The type of structural element (vertical vs. horizontal element). Usually, suspended horizontal elements require higher early-age strength for formwork removal, and all horizontal elements require more care in finishing.

Other factors to be considered before determining the specific percentages of these supplementary cementing materials (SCMs) to be used in concrete in a specific region include:

- The availability of the SCMs.
- The current percentage of fly ash or slag commonly used in local concrete operations/applications.
- The experience of the concrete producers and contractors with the use of SCMs in concrete.

The introduction of concrete incorporating percentages of fly ash or slag higher than those used in common concrete practice in a specific region may require training of personnel in the local construction industry including cement suppliers, concrete producers, contractors and testing laboratories.

4.3.1 All types of concrete applications

For all types of concrete applications, it is recommended to use:

In cold weather (the air temperature is at or below 5°C as defined by CSA A23.1):
Minimum 15% of SCMs (fly ash or slag or a mixture of both)

In hot weather (the air temperature is at or above 27°C as defined by CSA A23.1):
Minimum 25% of SCMs (fly ash or slag or a mixture of both)

Note: It is understood that for some types of applications and types of SCM, it is possible (and in some cases, it is required) to use much higher SCMs percentages in concrete than the above minimums, but for some other applications and types of SCMs, even the use of 15% might represent a challenge. However, the objective of the above recommended minimum percentages is to increase the average use of SCMs in cement and concrete in Canada from 10% to ~20% in order to reduce the GHG emissions per m³ of concrete produced, and also to increase the durability and service life of concrete, thus promoting sustainability.

4.3.2 Massive concrete structures, for which consideration is given to temperature rise caused by hydration of portland cement

The incorporation of high volumes of some fly ashes and slags in concrete is an effective way to significantly reduce the heat of hydration and consequently the risk of thermal cracking. Thus, it is recommended to use of as much fly ash and slag as possible in concrete for this type of application.

In order to significantly reduce the heat of hydration, it is recommended to use:

In cold weather:
Minimum 40% of fly ash Type F or CI, or a mixture of both, or

Minimum 50% of fly ash Type CH or slag, or a mixture of both

In hot weather:

Minimum 50% of fly ash Type F or CI, or a mixture of both, or

Minimum 65% of fly ash Type CH or slag, or a mixture of both.

However, it should be noted that for some type CH fly ashes and slag, even the use of 65% would not be enough to reduce the risk of thermal cracking. In this case, concrete mixtures should be evaluated for this particular property.

4.3.3 Concrete exposed to a sulphate environment

The SCMs contents to be used to produce a concrete resistant to sulphate attack depends on the type of SCM used, and the type of sulphate exposure (moderate or severe).

Regardless of the weather conditions, it is recommended to use:

Minimum 20% of fly ash Type F or CI, or a mixture of both, or

Minimum 35 to 55% of slag (the minimum being increased with an increased sulphate exposure severity, and increased Al_2O_3 content in the slag).

For fly ash Type CH (that is not produced and rarely used in Canada), the minimum percentages for sulphate resistance should be investigated.

It is also possible to produce a sulphate resistant concrete by using ternary blended cements.

4.3.4 Concrete made with reactive aggregates

CSA A23.2-27A recommended practice suggests an approach based on a risk analysis to select the minimum % of fly ash or slag to control alkali-silica reaction in concrete. The safe SCMs content depends on the reactivity level of the aggregate, the type of structure and its exposure conditions and its expected service life.

According to CSA A23.2-27A, regardless of the weather conditions it is recommended to use:

Minimum 25% to 35% of fly ash Type F or CI, or a mixture of both, or

Minimum 35% to 50% of slag

For fly ash Type CH (that is not produced and rarely used in Canada), the minimum percentages should be investigated for alkali-silica reaction resistance in accordance with CSA A23.2-28A.

It is also possible to produce a concrete resistant to ASR by using ternary blended cements. CSA A23.2-27A provides recommendations for the proportions of SCMs to be used in ternary blended systems to control ASR in concrete.

4.3.5 Structurally reinforced concrete exposed to chlorides with or without freezing and thawing cycling

The most effective way to produce concrete that is resistant to chloride ion penetration is by using SCMs and a low W/CM.

In order to produce a concrete with a coulombs value for chloride ion penetrability less than 1500 coulombs within 56 days, it is recommended to use:

Regardless of the weather conditions:

Minimum 30% of SCMs (fly ash, or slag, or a mixture of both).

The use of ternary blends with silica fume can also produce concrete with coulombs values less than the above maximum.

To achieve the above coulombs value, the concrete must be properly proportioned and well cured.

4.3.6 Hand finishing concrete flatwork exposed to a combination of deicing salts and freezing and thawing cycles

The resistance to de-icing salt scaling of concrete mixtures incorporating fly ash or slag still remains highly controversial. Indeed, numerous laboratory test data using the ASTM C 672 test procedure have indicated that concrete mixtures incorporating more than about 20% fly ash or 25% slag often perform unsatisfactorily when exposed to freezing and thawing cycles in the presence of de-icing salts. On the other hand, there are several reported cases of concrete structures incorporating significant amounts of fly ash that have performed well when exposed to de-icing salts in the field. So far, there is no clear explanation for this discrepancy, but it is believed that the ASTM C 672 laboratory test, which evaluates the deicing salt scaling resistance of concrete, is too severe for concrete incorporating SCMs. In fact, a recent study has shown that the BNQ procedure (standard test of the province of Quebec, Canada) simulates better the scaling resistance of the concrete incorporating SCMs compared to the ASTM procedure. This study has also shown that sidewalks in the city of Montreal made with 35% fly ash concrete in the spring and with 25% fly ash concrete in the fall (Type F fly ash) performed similarly to control concrete after being subjected to at least 20 cycles of freezing and thawing combined with the application of the deicer (11). Therefore, based on the actual data, it is recommended to use:

In cold weather:

Maximum 25% of fly ash Type F or CI, or a mixture of both, or

Maximum 35% of fly ash Type CH or slag, or a mixture of both,

In hot weather:

Maximum 35% of fly ash Type F or CI, or a mixture of both, or

Maximum 50% of fly ash Type CH or slag, or a mixture of both.

Table 4.3 Proposed minimum percentages (by mass of total cementitious materials) of fly ash and GGBFS for different concrete applications

| Type of applications or exposures | Cold weather | | | | Hot weather | | | |
|---|--------------|----------|----------------|----------|-------------|----------|----------------|----------|
| | Type F | Type CI | Type CH | Slag | Type F | Type CI | Type CH | Slag |
| All applications | 15 | 15 | 15 | 15 | 25 | 25 | 25 | 25 |
| Mass concrete | 40 | 40 | 50 | 50 | 50 | 50 | 65* | 65* |
| Exposed to Sulphate | 20 | 20 | - [†] | 35 to 55 | 20 | 20 | - [†] | 35 to 55 |
| ASR issues | 20 to 35 | 20 to 35 | - [†] | 35 | 20 to 35 | 20 to 35 | - [†] | 35 |
| CSA Class C-1 [‡] | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| Hand-finishing concrete flatwork exposed to chloride and freeze/thaw cycles | Max 25 | Max 25 | Max 35 | Max 35 | Max 35 | Max 35 | Max 50 | Max 50 |

* For some type CH fly ashes and slags, the minimum of 65% might not be enough and the minimum percentages should be investigated

[†] Minimum percentages should be investigated

[‡] Except hand finishing concrete flatwork

4.4 Examples of projects using fly ash and slag in concrete

The following table gives examples of projects that used moderate to high levels of SCMs in concrete.

Table 4.4 Examples of project requirements using fly ash and GGBFS in Canada

| Project | Element | Min 28-day strength, MPa | Exposure Class | Fly Ash (FA) or GGBFS percentages by total weight of cementitious materials |
|--|--|----------------------------|----------------|---|
| Parklane Development – Halifax, N.S. (16) | Columns and beams | 50 @ 120 days | F2 | 56% FA (Type F) |
| Purdys Wharf Development – Halifax, N.S. (67) | Caisson footings | 45 | C2 | 56% FA (Type F) |
| Confederation Bridge (100 year design life) (17) | All members. Substructure and superstructure | 70 @ 90 days | C1 | 15% FA (Type F) |
| | Massive elements – girder, slabs near piers | 70 @ 90 days | C1 | 29% FA (Type F) |
| Liu Center – UBC (18) | Walls, columns, footings | 25 | N | 50% FA (Type CI) |
| | Slab on grade exterior | | C2 | 33% FA (Type CI) |
| | Topping | | N | 35% FA (Type CI) |
| Bayview High-Rise Apartment – BC (19) | Parking slabs and slab bands | 35 (21 stripping strength) | C1 | 33% FA (Type CI) |
| | Slab on grade interior parking | 25 | C4 | 20% FA (Type CI) |
| | Slab on grade exterior | 32 | C2 | 20% FA (Type CI) |
| | Footings | 30 | N | 45% FA (Type CI) |

| Project | Element | Min 28-day strength, MPa | Exposure Class | Fly Ash (FA) or GGBFS percentages by total weight of cementitious materials |
|---------------------------------------|---|----------------------------|----------------|---|
| | Shear walls and columns (Foundations) | 40 (24 stripping strength) | N | 33% FA (Type CI) |
| | Topping and pads | 20 | N | 45% FA (Type CI) |
| York University – ON. (13) | Foundation walls and columns exposed to freeze-thaw | 30 | F2 | 50% FA (Type CI) |
| | Footings, columns, slabs (suspended and interior on grade) | 25, 30, 25 | N | 50% FA (Type CI) |
| TEFIII – UBC (20) | Footings | 30 | N | 55% FA |
| | Slab on grade (interior parking) | 35 | C1 | 25% FA |
| | Slab on grade exterior | 32 | C2 | 15% FA |
| | Walls and columns | 25-40 | N | 35% FA |
| Nicola Valley Institute – BC (21) | Foundations, footings, walls above grade, columns, interior slab on grade | 25-30 | F2 | 50% FA (Type F) |
| | Suspended slabs, beams | 25 | N | 33% FA (Type F) |
| | Exterior slab on grade | 32 | C2 | 20% max FA (Type F) |
| Shepherd Ave. Toronto, ON | Precast tunnel lines | 85 | C1 | 25% slag +8% SF |
| | Don Mills station | ? | ? | 50% slag |
| GTAA-Pearson Airport. Toronto, ON | All bridges and decks | 35 | C1 | 25% slag + T10SF |
| | Parking garage TI | 35 | C1 | 25% slag |
| BCE Tower Toronto, ON | Tower I, columns | 70 | - | 25% slag + T10SF |
| | Tower II, columns | 70-85 | - | 25% slag + T10SF |
| Skytrain Millenium Line Vancouver, BC | Caissons, footings | 35 | N | 30% FA |
| | Piers | 35 | C1 | 25% FA |
| | Precast box girders | 40 | C1 | 10% FA |

5. PRODUCTION AND PLACING OF CONCRETE

5.1 Production

This section discusses the effect of SCMs use on technical requirements such as equipment and operation (sequence of mixing) of ready-mix concrete plants.

The production of concrete incorporating SCMs should meet the CSA A23.1 requirements for production and delivery of concrete (CSA A23.1-00 Section 18: Production). However, the following should be taken into account, especially when using high volumes of SCMs (i.e. more than 30% fly ash, or 35% slag).

In general, fly ash has a relative bulk density much lower than that of cement (2.00 to >2.60 vs 3.15 for portland cement, and ~2.9 for GGBFS). Therefore, the silo and weighing scale volumes may need to be redesigned to accommodate larger volumes of powder (especially with high volumes of SCMs) or be prepared to deal with the possibility of double or even triple batching to make a load of concrete.

As all cementing materials are pneumatically introduced in the silos, and either dropped or augered to the weighing mechanism, there is a lot of potential dust, and again, due to the lightness of some products, the air pressures should be adjusted accordingly in the silos and in the weigh hoppers to prevent false weights.

It is preferred, but not always possible, to auger fly ash as it has a propensity to flow past gates. A slight incline to the augers is also preferable.

The CSA weighing tolerances are fairly clear that no cement should be under-batched as part of the usual tolerance. Most weighing devices these days allow the underweight of one constituent to be made up with an excess weight of the other. In this case the total weight of cement plus fly ash or slag will be in the CSA tolerance range, however the ratios will vary, especially in small batches. The weighing of fly ash or slag should follow that of cements in all cases (CSA A23.1 Clause 18.1.3.1) as most ready-mix concrete plants follow the practice of augered fly ash and free falling cement into the weigh hoppers.

5.2 Placing, finishing and stripping of concrete

Placing, finishing and formwork removal of concrete incorporating SCMs should follow CSA A23.1 requirements. This section mainly discusses the effect of SCMs on parameters affecting the placing, finishing and stripping characteristics of concrete, such as pumpability, bleeding, plastic shrinkage and setting times.

5.2.1 Placing

The use of fly ash and slag generally increases workability, and decreases segregation and bleeding of concrete. This makes the concrete easier to place and fill forms. Published data have shown that such concrete is relatively easy to pump, place, consolidate and finish.

Ternary blends of cement, fly ash/slag and silica fume with superplasticizers are very cohesive mixtures and tend to present marginal placing difficulties, particularly by bucket and crane.

Concrete made with high volumes of SCMs (i.e. more than 30% fly ash, or 35% slag) will often be supplied with a slump of 150 to 200 mm (using superplasticizers) and is thus very workable (when the slump is low, these concretes tend to be very cohesive). Only a minimum of vibration is required to consolidate such concrete. In construction of high wall sections, external vibration will mobilize the concrete in lower lifts, and the formwork must be designed for a full liquid head. Internal vibrators are acceptable, however the concrete must not be over vibrated.

5.2.2 Finishing

Concrete with moderate levels of SCMs (15 to 25%)

It is the general view of finishers that the use of moderate levels of SCMs makes the finishing of concrete slabs easier due to the increase of workability and the volume of paste. In fact, some finishers will complain if SCM is not used in concrete.

Concrete with high volumes of SCMs (>30 to 35%) and low W/CM

Concrete with low W/CM, and incorporating high volumes of SCMs can present problems with finishability. The problems are in most cases due to the impact resulting from reduced water content in the mix and thus, less bleed water being available to condition the surface of the fresh concrete. The effects of the low bleed water can be mitigated if diligent attention is made to control the amount of surface drying on the fresh concrete. By attentive care and by utilizing a fog spray, evaporative inhibitor or midrange water reducer (compatible with the fly ash system, and that can keep the workability for longer), the surface water sheen can be replenished and the lack of moisture that results in finishing difficulties can be eliminated or at least significantly reduced.

The use of high volumes of SCMs in concrete also increases setting time (which can be a positive attribute in warmer weather) and delays finishing operations. Alternatively, set accelerators (non-chloride) can be used to compensate for the delays in setting time.

Slabs exposed to a combination of chlorides and freezing and thawing cycles

Regardless of the SCMs content in concrete, the following provides some guidance on finishing in order to improve the scaling resistance of concrete:

- Wait until bleeding is stopped before final finishing operations
- Keep surface damp but not wet between initial strike off and final finish
- Use minimal working of the surface during finishing
- Avoid use of steel trowels wherever possible
- Use wood trowel/float
- Apply curing after final finish – membrane or moist (curing compound was found to increase the scaling resistance of fly ash concrete)
- If it is not possible to allow 1-month of “maturing” before first freeze or salt application, then use a minimum amount of SCM.

5.2.3 Stripping

Form removal or stripping is an operation that most of the time is contingent upon realizing a pre-defined insitu compressive strength for the element. In the cases of vertical elements, a value of 6 to 10 MPa is usually required prior to stripping the forms. Concrete will easily achieve this stripping strength at 1-day or earlier even with high volumes of SCMs.

For suspended slabs, a higher strength is required (typically 70 – 75% of the design 28-day strength). Concrete with moderate levels of SCMs (up to 25%) will easily achieve the required stripping strength at early-age. For concrete with high volumes of SCMs (> 30 to 35%), a judicious proportioning of the concrete mixture is required to achieve a required stripping strength in a timely manner. As mentioned in Chapter 3, this usually requires a reduction in W/CM, the incorporation of silica fume, or the use of some non-chloride accelerators, especially in cool weather. Structural designers may permit sooner stripping time for suspended slabs if properly re-shored during stripping.

6. CURING

6.1 Definition

Curing is defined in CSA A23.1 as the "maintenance of a satisfactory moisture content and temperature in concrete for a period of time following placing and finishing so that desired properties may develop".

6.2 Curing objectives

There are three criteria that should be met by curing.

- (1) A satisfactory moisture content needs to be maintained so that hydration of the cementitious material continues long enough so that the required strength, durability and impermeability of the concrete is achieved and shrinkage induced cracking is minimized.
- (2) The concrete and ambient temperatures affect the rate of hydration and the ultimate strength of the concrete. Suitable minimum and maximum temperature limits are necessary.
- (3) The temperature differentials within the concrete and between the surface of the concrete and the ambient temperature need to be controlled so that deleterious thermal cracking is eliminated. The permissible temperature gradients are dependent on the size and geometry of the concrete section. As mentioned in Chapter 3, the use of fly ash and slag generally reduces the risk of thermal cracking.

6.3 Curing regimes

According to CSA A23.1, three types of curing regimes are allowed; these are basic, additional, and extended curing (Table 6.1).

Table 6.1 Allowable curing regimes (CSA A23.1)

| Curing regime | Name | Description |
|---------------|------------|--|
| 1 | Basic | 3 d at $\geq 10^{\circ}\text{C}$ or for a time necessary to attain 40% of the specified strength. |
| 2 | Additional | 7 d at $\geq 10^{\circ}\text{C}$ and for a time necessary to attain 70% of the specified strength... |
| 3 | Extended | A wet curing period of 7 d. The curing types allowed are ponding, continuous sprinkling, absorptive mat or fabric kept continuously wet... |

For formed components, leaving forms in place until the above criteria are met complies with the intent of basic and additional curing regimes. If forms are removed earlier, then concrete components should be wrapped in plastic, or coated uniformly and at the manufacturer's recommended rate of application with a high quality membrane curing compound or be kept wet by the application of water through soaker hoses or fog sprays.

For flatwork maintenance, a moist condition is needed, not only to promote hydration but also to reduce drying shrinkage that could lead to excessive cracking. Moisture can be applied by fog sprays or by covering with pre-soaked burlap or proprietary mats that hold moisture. Covering the soaked coverings with polyethylene sheets can reduce water loss. Weather conditions requiring special protection of flatwork can develop quickly. Pre-planning should take place before concreting starts so that materials and equipment are on site when needed.

The following table gives the type of curing required for each class of exposure and each type of concrete with regard to SCMs contents as defined by CSA A 23.1.

Table 6.2 Curing regime required for different classes of exposure

| Class of exposure* | Not HVSCM concrete | HVSCM2 [†] | HVSCM1 [‡] |
|--------------------|--------------------|---------------------|---------------------|
| C-XL | 3 | 3 | 3 |
| C-1 or A-1 | 2 | 2 | 3 |
| C-2 or A-2 | 1 | 2 | 2 |
| C-3 or A-3 | 1 | 2 | 2 |
| C-4 or A-4 | 1 | 2 | 2 |
| F-1 | 2 | 2 | 3 |
| F-2 | 1 | 2 | 2 |
| N | 1 | 2 | 2 |
| S-1 | 2 | 2 | 3 |
| S-2 | 2 | 2 | 3 |
| S-3 | 1 | 2 | 2 |

* Refer to Table 4.2.

[†] Concrete with SCMs contents meeting the following equation $FA/30 + S/35 > 1$ (FA: %fly ash, S: %Slag)

[‡] Concrete with SCMs contents meeting the following equation $FA/40 + S/45 > 1$ (FA: %fly ash, S: %Slag)

There is no difference between curing a portland cement concrete and a concrete with SCMs contents less than 30 to 35%. For concrete with higher volumes of SCMs, the curing regime becomes more stringent. Caution: Although there is no difference in specified curing for conventional concrete and SCM concrete (with SCM contents less than 30 to 35%), the SCM concrete must be cured (as specified) as it is less forgiving than conventional concrete.

7. QUALITY CONTROL OF CONCRETE INCORPORATING SCMs

This chapter presents recommendations for the quality control (QC) to be applied when concrete containing SCMs is specified. The details of the QC will vary with the specific project.

7.1 How QC is defined by CSA Standards

In CSA A23.1 – 2000 Section 17.1.1, it is stated that the owner is responsible for evaluating the quality of the concrete. The supplier’s responsibility is defined in CSA A23.1 – 2000 Table 13 as certifying that the ready-mixed plant and materials comply with the Standard and that the mixture proportions will produce the “specified quality”.

The required tests and their frequency on the SCM materials (such as LOI and 45µm sieve) and on the concrete (such as slump, air content and compressive strength) are found in CSA A 3000, and CSA A23.1, respectively.

7.2 Quality control of concrete incorporating less than 30% fly ash or 35% slag

Concrete containing SCMs less than the above values will require similar quality control to that applied to portland cement concrete.

7.3 Quality control of concrete incorporating more than 30% fly ash or 35% slag

For this type of concrete, the additional requirements for QC include verifying the following:

- A requirement for HVSCM1 ($FA/40 + S/45 > 1$) that the maximum W/CM for a particular class of exposure be 0.05 less than the stated maximum for portland cement concrete (see Table 4.1);
- Increased curing requirements (see Table 6.2);
- For reinforced concrete elements exposed to moisture and air, with depths of cover less than 50 mm, the W/CM should not be greater than 0.40 for HVSCM1 ($FA/40 + S/45 > 1$) and not greater than 0.45 for HVSCM2 ($FA/30 + S/35 > 1$);
- The need for a pre-qualification testing (trial mix) program.

7.4 QC recommendations for concrete incorporating SCMs

Summary of the QC recommendations for concrete incorporating SCMs is given in Table 7.1 in terms of a checklist for quality control actions.

7.4.1 On the SCM itself

Obtain mill certificates from the SCM producer with each shipment of SCM to the plant. Determine compliance with CSA A3001. Request additional information on the uniformity of the SCM – for fly ash, this can be for LOI, % retained on 45µm sieve for Type F ash with the addition of CaO for Type CI and CH; for slag this may be only % retained on 45µm sieve. For new sources require historical data.

7.4.2 Review of the proposed mixture proportions

Mixture proportion review is the first step in effective QC. The review is best done by a materials engineer familiar with the performance of the particular SCM. Assure that the proposed properties comply with the specification; this may necessitate submission of trial mix performed under controlled conditions in the laboratory or other test data. If the project requires HVSCM, assure that the requirements outlined in 7.3 are met. Assure that the strength data available permits estimation of the long-term strength from early age results. Note: As mixture proportions for any given concrete plant may become proprietary, it may be necessary for the concrete supplier to provide a sample of concrete on which the Owner can satisfy himself that the specifications are met.

7.4.3 QC by the ready-mixed producer

In addition to conducting the pre-qualification trials in 7.4.2, and determining the compatibility and performance of the materials, the ready-mixed producer may need to intensify the QC testing during early stages of concreting with each mixture proportion. Additional air content tests will be required, particularly if fly ash with a high LOI is used.

7.4.4 QC by the contractor

Experience with the implementation of SCM concrete on projects dictates that an initial field trial to evaluate the behaviour of the concrete using actual ready-mixed production is desirable and can pay dividends. This can take various forms, and can be combined with qualification testing of the mixture proportions, including early age strength testing. It may involve:

- Using project concrete for the initial field trial. This commonly is done in the footings, which are not normally critical concrete and are usually of lower strength than the structural concrete.
- Placing one or more loads of the SCM concrete and observing its plastic properties. The placers may find that it is stickier than normal concrete and does not bleed.
- Troweling the surface of the concrete to get experience with its feel under the trowels.

Table 7.1 Checklist for Quality Control Action by Parties

| Function | Owner | SCM Producer | Ready-Mixed Producer | Contractor |
|--|--|---|--|--|
| Mix design(s) | Review as to compliance with Specs. and representative nature of supporting test results. Check that required SCM replacement is achieved. | Provide recommendations for amount of cementing materials required at SCM replacement levels for equivalent strength. | Conduct trial mixes in laboratory. Prepare mix design(s). | Co-ordinate review. Assure that approval from Owner is obtained. |
| Pre-qualification program on mix design(s) | Review results. Assure that representative age:strength curves are available so that site early age strengths can be checked. | | Conduct trials in field at early stages of concreting. | Arrange for trial mixes in field. Use the trials to develop early-age strength test calibration if required. |
| Initial field trial to performance of mix's plastic properties | Witness site trials | | Co-operate with contractor in conducting trials. | Arrange for program. Involve placers and finishers. |
| Testing during initial concreting | Assure that testing to CSAA23.1, 17 is conducted. Require increased testing during initial concreting and for cases where exposure is Class C1, C2, or F1, F2. | | Increase QC testing of air content. | Manage finishing crew timing if reduced rate of bleeding and slower setting time expected. |
| Mill certificates | Review | Provide submittal, which includes data on uniformity of LOI and 45µm. Advise parties if there is a shift in properties. | Review and adjust QC and mix design according to any shifts in SCM properties. | Co-ordinate distribution of results |
| In situ strength monitoring | | | | Conduct tests if data on early strength is a requirement |
| Review QC test results | Conduct review. Assure that other parties are aware of results | | | |

8. CONCLUSIONS AND RECOMMENDATIONS

The use of fly ash and slag in concrete not only reduces the GHG emission signature of concrete, but also increases the performance and durability of concrete in most applications.

In terms of the properties of fresh concrete, the use of fly ash and slag generally increases the workability, pumpability, and easy of placing of concrete. It increases cohesiveness, and thus reduces the bleeding and segregation of concrete. It reduces the heat of hydration, and consequently the risk of thermal cracking. However, when used in high volumes (generally > 30 to 35%), it delays the setting times (especially for Type F ash), and significantly reduces the bleeding of concrete (especially for concrete with low W/CM), and these generally, create finishing problems for flatwork concrete. Some solutions to overcome these problems are presented in this document.

With regard to the mechanical properties of concrete, the use of fly ash and slag generally decreases strength at early ages (up to 28 days, depending on the type of SCM and the type of fly ash used), but increases it at later ages. SCMs also decrease the drying shrinkage and the creep of concrete at later ages. The reduction in early-age strength is more critical when high volumes of SCMs are used, especially in horizontal concrete elements. This can be overcome by using judicious concrete mixture proportions, such as optimizing the SCM content, reducing the W/CM, using appropriate admixtures, or adding silica fume.

With respect to the durability characteristics of concrete, the use of fly ash and slag increases the corrosion resistance of concrete and increases the sulphate and ASR resistance of concrete (when used with the appropriate percentages). However, it decreases carbonation resistance if the concrete is not well cured and/or the W/CM is not reduced. Also, the use of high volumes of fly ash and slag decreases the scaling resistance of concrete if the finishing and curing of the slabs is not carefully done. For these two latter parameters (carbonation and scaling), further research is still needed.

This Best Practice Guide shows that concrete incorporating fly ash and slag in proportions less than 20 to 30%, and 25 to 35%, respectively, is generally considered equivalent to portland cement concrete in terms of the requirements for production, curing and quality control. However, it should be mentioned that it is critical that these requirements be met for concrete with SCMs. For concrete incorporating higher volumes of fly ash and slag, additional measures are required and the type of curing regime required for each class of exposure is provided, as well as some recommendations for production and quality control. If this Best Practice Guide is followed, then the owner should be provided with good durable concrete structures for both lower (conventional) and high volume SCM use.

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