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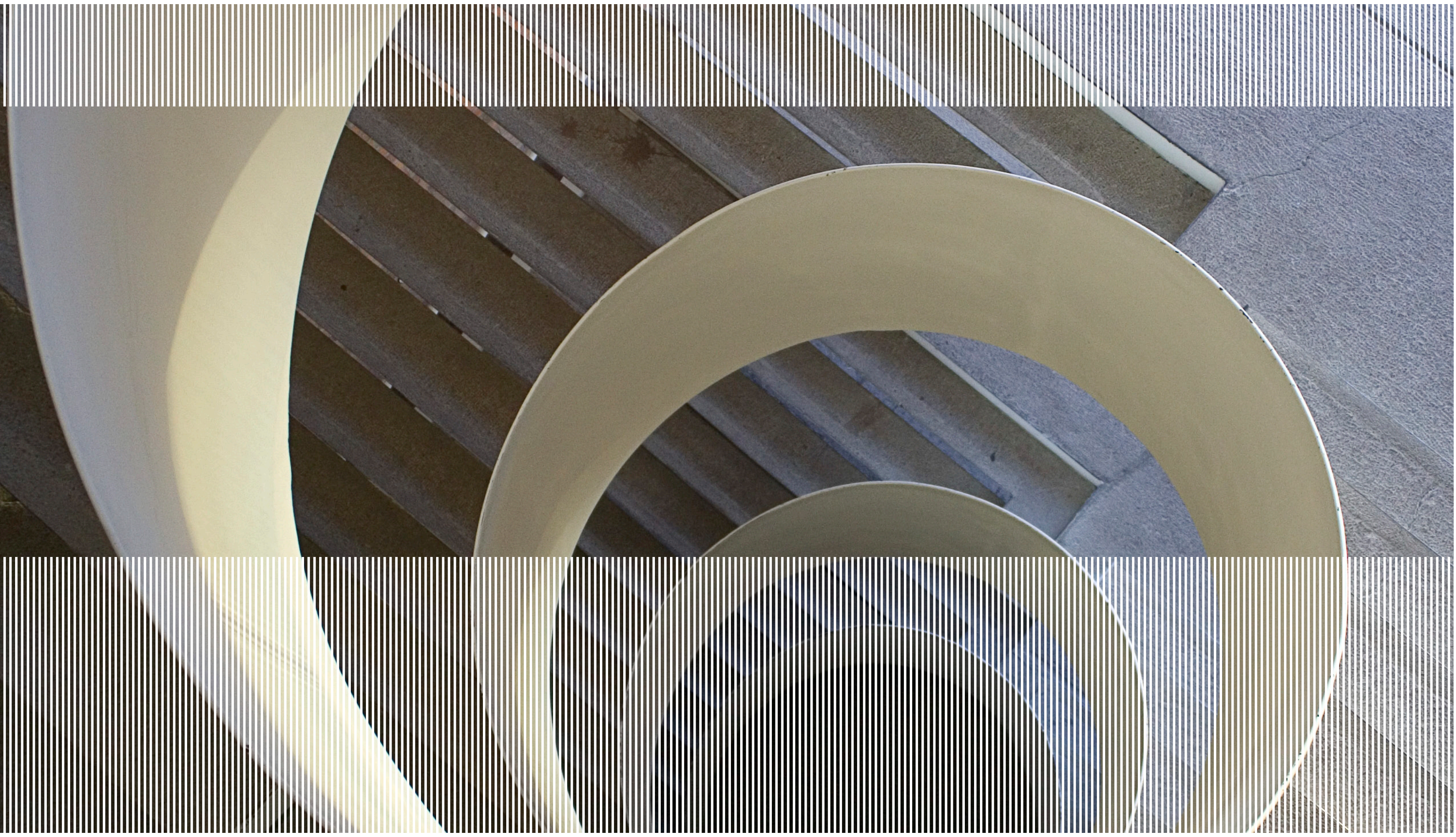
A literature study of the advantages and disadvantages

COIN Project report 18 - 2010



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Preface

This study has been carried out within COIN - Concrete Innovation Centre - one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfil this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %).

For more information, see www.coinweb.no

Tor Arne Hammer
Centre Manager

Summary

In this literature study it has been focused of the use of ASTM Class F fly ash in concrete, as a part of blended cement or used directly into concrete mixer. There were many articles that highlight the good properties of the use of fly ash, but few with the connection between fly ash blended cement and fly ash blended concrete and field construction. The study takes up both the advances and the drawbacks with use of fly ash cement.

One of the important advantages with fly ash concrete is the resistance to alkali aggregate reaction (AAR). Increasing AAR because of fly ash or increased fly ash content is not registered by any authors in this literature study. Several successful field constructions with high volume Class F fly ash concrete are mentioned. Even if the use of fly ash has a lot of advantages there always will be events of less favourable experience, because of different cement types, fly ashes, admixtures, aggregates, environment and temperature. However, there are few examples of poor field constructions with fly ash concrete. Perhaps this is because of its good properties of the fly ash concrete used in the constructions, or the reason is no one wants to report failed projects.

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1 Introduction

The background for this study was to find out what we know so far in the use of fly ash in concrete. What do we know about the advantages, disadvantages, field constructions, fly ash blended cement or fly ash blended concrete and experience with respect to fineness. This literature study focuses of the use of the low calcium fly ash ASTM Class F / EN 197-1 Type V. Much of the information is collected from the experience from USA and Canada, because of their long experience with fly ash in concrete.

Fly ash from power plants became available as early in the 1930s[1]. In the U.S. the study of fly ash for use in hydraulic cement concrete began at about that time. In 1960s a new generation of coal fired power plants was built, that produce a finer fly ash with lower carbon content. In addition fly ash containing high levels of calcium oxide became available (Class C fly ash).

According to U.S. dept of Transportation federal Highway Administration all the fly ash used in the US before 1975 was Class F[2].

The current annual world-wide production of coal ash is estimated to be 700 million tonnes, of which at least 70 % is fly ash, i.e. fine coal ash which is suitable for use as a pozzolan in cementitious systems[3]. Approximately 80 % of the coal ashes produced today end up either in low-value applications such as landfills and base courses for roads, or simply disposed of by ponding and stockpiling.

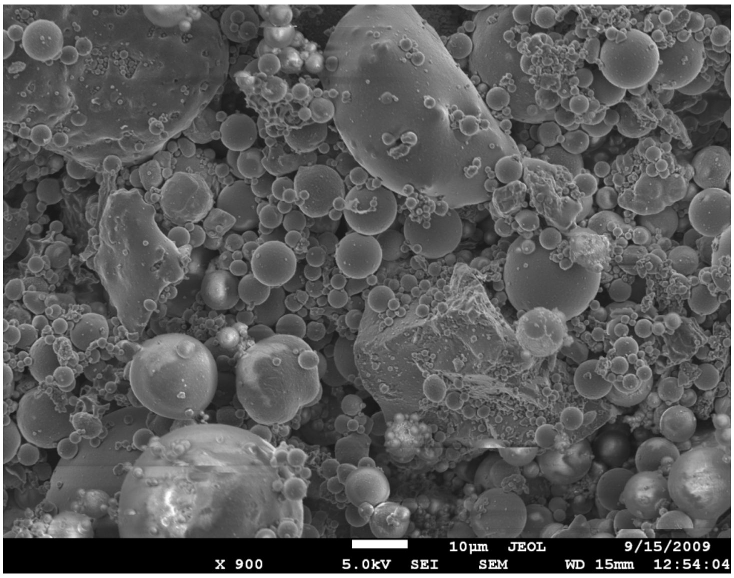

Figure 1. Typical fly ash particles in a Class F fly ash (Norcem R&D)

Fly ash is a by-product of the combustion of pulverized coal, usually from coal-fired power plants[1]. Fly ash solidifies in the exhaust gases and is collected by electrostatic precipitators or filter bags. According to American Concrete Institute ACI 116R fly ash is "the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal system". It has a glassy structure and is generally spherical particles (figure 1) with fineness usually in the same range like cement. Modern coal-fired power plants, that burn coal from a uniform source, generally produce very consistent fly ash, will slightly variation in size, chemical composition, mineralogical composition and density. According to NS-EN 197-1 it is only allowed to use fly ash from electrostatic or mechanical precipitation of the flue gas from kiln fired with coal.

Fly ash is a pozzolan. According to ACI 116R defines "pozzolan" as "a siliceous or siliceous and aluminous material that itself possesses little or no cementitious value, but that will, in finely divided form and in presence of moisture, chemically react with calcium hydroxide (CH) at ordinary temperatures to form compounds having cementitious properties; there are both natural and artificial pozzolans"[1]. All fly ash exhibit pozzolanic properties to some extent; however some fly ash display varying degrees of cementitious value without the addition of CH or hydraulic cement.

Fly ash in concrete reacts with the hydrating hydraulic cement in the following ways[1]:

- CH and alkali hydroxide, which are released into the pore structure of the paste, combined with the pozzolanic particles of fly ash forming a cementing medium.
- Heat generated by the hydration of hydraulic cement helps initiate the pozzolanic reaction and contributes to the rate of the reaction.

The chemical composition and physical characteristics of the fly ash from a coal-fired furnace are controlled by the type of coal and the processing conditions of the furnace[3]. These vary not only from one plant to another but also within the same plant. Variations in the chemical composition of fly ashes are, therefore natural. However, the pozzolanic properties of the fly ash are not governed so much by the chemistry but by the mineralogy and particle size of the ash. It may be noted that modern coal-fired thermal power plants generally produce good quality fly ash that is characterized by low carbon and high glass content, with 75 % or more particles finer than 45 µm. The pozzolanic activity of the fly ash is greatly influenced by the amount and composition of the glass phase present. The typical amount of glass phase is 60-90 %, and the reactivity of the glass being generally dependent on the calcium content.

The composition can vary significantly, but fly ash consists mostly of SiO_2. The SiO_2 can be amorphous (glassy and rounded) and crystalline (sharp and pointed)[1]. The largest fraction of fly ash consists of glassy spheres of two types: solid and hollow (cenospheres). The amorphous glassy particles are the primary contributor to the pozzolanic reaction.

The most-often-used specification for fly ash is ASTM C 618 that defined two classes of fly ash: Class F and Class C. EN 197-1 has another definition, Type V and W (table 1). The main difference between these classes is the amount of calcium, silica, alumina and iron content (table 1 and 2). The chemical properties of the fly ash are largely influenced by the chemical content of the coal burned. In general the burning of anthracite and bituminous coal produces Class F, and the burning of lignite or subbituminous coal produces Class C. Both fly ashes are pozzolanic, which means that a siliceous or an aluminosiliceous material reacts with the calcium hydroxide (CH) to form cementitious compounds. Class F needs cement in order to react. When the portland cement reacts with water (hydraulic reaction), calcium silicate hydrate (CSH) and CH are formed. CSH makes the strength and CH fills the voids. The pozzolanic reaction starts later than the hydraulic reaction. The fly ash reacts with the CH and forms the same type of CSH. The hydrated cement paste gets a less permeable pore structure and an additional improvement of the strength[4].

High volume fly ash concrete practice in North America is based on the use of fly ash as a separately-batched ingredient to the concrete mix[3]. Blended cements are produced at cement plants, and have an additional advantage that their physical and chemical characteristics, such as fineness and sulphate content, can be adjusted to optimize the properties of the blended product. Until recently most of the world's standards for blended cements limited the fly ash content to a maximum of 40 % by mass. But today ASTM C 1157-03 a performance-based standard for hydraulic cements does not restrict the amount and type of blending materials as long as the cement meets certain performance characteristics. In Europe CEM IV/B cement with a content of pozzolanic materials including fly ash up to 55 % is permitted according to EN197-1, 2000.

Table 1. Some definition of fly ash types according to EN 197-1 and ASTM C618 [3 4 5]

	Low calcium fly ash	**High calcium fly ash**
Fly ash from	Bituminous coal and anthracite	Subbituminous and lignite
Reaction characteristic	Pozzolanic	Pozzolanic and hydraulic
Definition by EN 197-1	**Type V** **Siliceous fly ash**	**Type W** **Calcareous fly ash**
	≤ 10 % reactive CaO ≥ 25 % reactive SiO_2 < 5 % LOI <1 % free lime	≥ 10 % reactive CaO ≥ 25 % reactive SiO_2 when CaO is 10-15 %. If CaO >15 % the compressive strength ≥ 10 MPa at 28 days (NS-EN 196-1) < 5 % LOI
Definition by ASTM C 618	**Class F**	**Class C**
	$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70$ % Free moisture, max: 3,0 % LOI, max: 6,0 % SO_3, max: 5,0 % CaO, max: No limit Amount retained when wet sieved on 45 µm: Max. 34 %	$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 50$ % Free moisture, max: 3,0 % LOI, max: 6,0 % SO_3, max: 5,0 % CaO, max: No limit (Note: CaO > 10 %) Amount retained when wet sieved on 45 µm: Max. 34 %

Table 2. Typical values for fly ash Class F and C[16].

	Typical values (wt.-%)	Class F	Class C
SiO_2	35-60		
CaO	1-35	< 15 wt.-%	>15 wt.-% (In Canada: Class C1: 8-20 % Class C > 20 %)
Fe_2O_3	4-20		
Al_2O_3	10-30		

2 Description of the method

The literature study was based on net searching using the words "fine, coarse, fly ash, high volume fly ash, concrete":

- www.sciencedirect.com
- www.scienceindex.com
- Wikipedia
- Google
- Yahoo!
- ACI
- World of Knowledge (WOK), eLibrary, internal service by Heidelberg Technology Center
- CANMET

In addition articles from several proceedings of the International Conferences on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete by CANMET / ACI have been read.

3 Results

It is a lot of articles about fly ash concrete, but most of them are based on laboratory research and not from the field. Laboratory environment and laboratory samples of mortar and concrete will not be exactly the same as concrete samples at a field site or in a real structure. There is little literature of concrete from field sites with good description of the materials used. The result of the study is divided into advantages, disadvantages, field experience and coarse / fine fly ash. Some of chemical analyses of the fly ashes are mentioned in the reference list.

3.1 Advantages

V. M. Malhotra and P. K. Mehta compares high volume fly ash concrete with conventional Portland cement concrete in a table shown below[3]:

Table 3. Properties of high volume fly ash concrete according to Malhotra and Metha.

Flowability / Pumpability	Easier
Workability / Compactability	Easier
Bleeding	None or negligible
Finishing	Quicker
Setting time	Slower up to 2 hours
Early strength (up to 7 days)	Lower but can be accelerated
Ulimate strength (90 days +)	Higher
Crack resistance: • Plastic shrinkage • Thermal shrinkage • Drying shrinkage	 Higher (if unprotected) Lower Lower
Resistance to penetration of chloride ions	Very high (after 90 days)
Electrical resistivity	Very high
Durability: • Resistance to sulphate attack • Resistance to alkali-silica expansion (ASR/AAR) • Resistance to reinforcement corrosion	 Very high Very high High
Abrasion resistance Endurance Limit	Similar Similar
Cost: • Materials • Labour • Life cycle	 Lower Similar Very low
Environmental friendliness with respect to CO_2 emission	Very high

3.1.1 Economical

There hopefully will be a lot of fly ash available in the future. Land fill and storing of the fly ash are not environmentally friendly. The world production of fly ash is approximately over 600 M tonnes annually, and only about 10 % of the fly ash is used in concrete. According to Wikipedia 65 % of the fly ash produced from coal power stations is disposed of in landfills.

3.1.2 Environment

In the past the fly ash was generally released into the atmosphere, but today the fly ash has to be placed in landfills or stored at the power plants[1]. The use of fly ash as partial replacement of clinker in cement or as direct addition to the concrete solves an environment problem for the milieu and the power plant. The fly ash as a substitute of the cement will also give a milieu profit by reducing CO_2 emission in the cement production process, and an energy saving when fly ash replaces some of the energy-intensive produced cement. Production of 1 ton cement generally produces 1 ton CO_2 (Norcem Brevik: 0.7 ton CO_2/ ton cement).

Another benefit is the reduction of toxic metals and radon in fly ash deposed into ponds and landfills[3]. Fly ashes may contain very small amounts of toxic metals that are leachable. Incorporation of fly ash in concrete solves this problem because hydration products of both Portland cement and blended Portland cement can form complexes that permanently tie up the toxic cations released by fly ash.

3.1.3 Workability

Fly ash improves the workability of the concrete[6]. Workability refers to the ease of handling, placing and finishing of fresh or "plastic" concrete. The fly ash concrete is more workable than a plain cement concrete at equivalent slump. Less water is needed for the same slump, the concrete gets more cohesive and the occurrence of costly segregation decreases. The amount of fines will increase and make the concrete more workable and a more complete compaction.

According to ACI Bulletin the fly ash particles fill the voids between aggregates, and the spherical particle shape acts as a lubricant in the pump line[7]. Another explanation of the better workability is the greater paste volume when the cement is replaced 1-to-1. The fly ash occupies 30 % greater volume than the cement.

Concrete pumping is made easier. Form filling becomes easier. Fly ash concrete is more responsive to vibration. Segregation, voids, rock pockets are reduced because of increased cohesiveness and workability.

3.1.4 Water demand

The water demand and workability are controlled by particle size distribution, particle packing effect, and smoothness of surface texture[3].

As mentioned above the fly ash replacing some of the cement will increase the paste volume[8]. The fly ash concrete is more workable and less water is needed for the same slump.
Although increased fineness usually increases the water demand, the spherical particle shape of the fly ash lowers particle friction and offsets such effects[2].

The use of fly ash as a partial replacement for Portland cement will usually reduce water demand[7].

3.1.5 Bleeding and segregation

The bleeding of high volume fly ash concrete ranges from negligible to very low because of its low water content[3]. It is important to cure the concrete as soon as possible after placement. In flat work, the use of foggers at the job site is strongly recommended in order to prevent plastic shrinkage cracking.

Less water is needed for the same slump, the concrete gets more cohesive and the occurrence of costly segregation reduces[6].

Using fly ash in concrete mixtures usually reduces bleeding[7]. The use of fly ash compensate for a deficiency of fines in the mixture, at the same time, it acts as a water-reducer to promote workability at lower water content. This results in adequate cohesion and plasticity with less water available for bleeding.

Using fly ash concrete mixtures usually reduces bleeding by providing greater fines volume and lower water content for a given workability[2]. Increased fineness usually increases the water demand, the spherical particle shape of fly ash lowers particle friction and offsets such effects. Concrete with relatively high fly ash content will require less water than non-fly ash concrete of equal slump.

In 1985, CANMET developed a concrete with large volumes of fly ash[8]. When building the Liu Centre for the Study of Global Issues it was used high-volume fly ash concrete in part of the building to demonstrate the potential of this type of concrete with 50-55 % fly ash. The bleeding of this type of concrete ranges from being very low to negligible due to the very low water content (w/cm<0,35).

3.1.6 Heat of hydration

In large concrete block, 3.05 x 3.05 x 3.05 m, the maximum temperature reached in the middle of the block was 54°C (a rise of 35°C when the start temperature was 19°C)[3]. The control concrete incorporating ASTM type I Portland cement has a temperature rise of 65°C.

A slower reaction rate of fly ash, when compared to hydraulic cement, limits the amount of early heat generation and the detrimental early temperature rise in massive structures[1].

The high-volume fly ash concrete used in the Liu Centre show a rather low autogenous temperature rise[8]. Several investigations have shown that the autogenous temperature rise of high-volume fly ash concrete was about 15-25°C less than that of a reference concrete without fly ash. This is an advantage where thermal gradient and stress are an issue.

Concretes have been made using high-volume fly ash blended cements (55 % Class F fly ash), one coarse and one finer fly ash and concrete in which the same fly ash had been added as a separate material at the mixer[9]. Blaine of the fly ashes were respectively 196 and 306 m^2/ kg. Reference concretes (ASTM type III cement and laboratory made normal Portland cement) without fly ash were also made. The autogenous temperature rise was significantly lower and slower for the concrete incorporating fly ash (both fly ash blended cement and fly ash to the concrete mixer) than for the control concretes without fly ash.

3.1.7 Drying shrinkage and creep

The drying shrinkage of concrete is directly influenced by amount and by the quality of the cement pasta present[3]. It increases with an increase in the cement paste content of the concrete mixture, and with the water content of the paste. The water-reducing property of fly ash can be advantageously used for achieving a considerable reduction in drying shrinkage of concrete mixtures.

Drying shrinkage strain of high-volume fly ash concrete was comparable to, or lower than ordinary concrete[10]. Creep strain is lower for high-volume fly ash concrete than ordinary concrete, probably due to unreacted fly ash particles acting as fine aggregate, and thus providing increased restraint against creep. The very low water content of the concrete makes some contribution to the low creep strains.

Concretes have been made using high-volume fly ash blended cements (55 % Class F fly ash), one coarse and one finer fly ash and concrete in which the same fly ash had been added as a separate material at the mixer[9]. The drying shrinkage strain of the tested concretes, were low. The concrete made with blended cement has lower drying shrinkage than the concretes in which the fly ash had been added at the mixer.

3.1.8 Permeability

Permeability is defined as the coefficient representing "the rate at witch water is transmitted through a saturated specimen of concrete under externally maintained hydraulic gradient"[6].
Permeability is inversely linked to durability, the lower permeability the higher the durability of concrete. Testing has shown that properly proportioned concretes using a combination of fly ash, normal or high-range water reducing admixtures, and air entraining admixtures have the ability to produce the same low levels of permeability as latex modified and silica-fume concretes.

Permeability of concrete is governed by many factors such as amount of cementitious material, water content, aggregate grading, consolidation and curing efficiency[1]. CH liberated by hydrating cement is water soluble and may leach out of hardened concrete, leaving voids for ingress of water. Through its pozzolanic properties, fly ash chemically combines CH with water to produce CSH, thus reducing the risk of leaching CH. When fly ash concrete is properly cured, fly ash reaction products partially fill in the spaces originally occupied by mixing water that were not filled by the hydration products of the cement, thus lowering the concrete permeability to water and aggressive chemicals.

Fly ash increases the cementitious compounds, minimizes water demand and reduced bleed channels, all of which increase concrete density. By the reaction of fly ash and CH to CSH, a reduction of bleed channels, capillary channels and void spaces occurs. The small particles of fly ash will fill in the tiniest voids and increase the density of the concrete. When the amount of CH decreases, the resistance to weak acids, salts and sulphates increase.

The water permeability of the high-volume fly ash concrete used in the Liu Centre is very low[9]. Test of 50 mm thick concrete discs under unaxial flow conditions with a uniaxial pressure of 2.7 MPa indicate permeability less or equal to 10^{-13} m/s.

Concrete specimens cured at 20°C the permeability of fly ash concrete (50 % Class F fly ash) was lower than for equivalent grade concrete with no fly ash[11]. When the curing temperature was reduced to 5°C the permeability of the fly ash concrete was observed to increase and there where little difference between the fly ash and control concrete. The permeability of the fly ash concrete is clearly more sensitive to the duration of the moist curing period when curing at lower temperatures.

3.1.9 Alkali aggregate resistance

In Norway the alkali aggregate reaction (AAR) problem is solved with use of:

- CEM I and alkali ≤ 3 kg alk/m^3.
- CEM II A/V and alkali ≤ 6.5-7 kg alk/m^3 dependent of production site. The cement is a blended cement with 20 % Class F fly ash.
- CEM II/B-S with ≥ 32 % slag and alkali ≤ 4 kg alk/m^3.

AAR is a serious problem in North America[3]. It is well accepted practice to use pozzolanic admixtures that are quite effective in controlling the expansion due to AAR. In California, the California Department of Transportation requires that mineral admixtures like fly ash should be used in an amount that is at least 25 % of the cementitious material in all concrete used for the construction of state-funded highway project. Studies at CANMET have shown that, with high volume alkali Portland cement and reactive aggregate, the use of high volume fly ash concrete can effectively reduce the expansion due to AAR. The reduction in expansion results from low permeability, alkali-dilution effect due to the reduced cement content, the reduction in the pH of the pore fluid due to the pozzolanic reaction, and a change in composition of CSH which allows more alkalis to be trapped in the CSH structure.

Class F fly ash in the mix design reduces the alkali aggregate reaction (AAR)[6]. Larger quantities of Class C fly ash than Class F may be required to control a reaction. The decrease in AAR comes from the fact that Class F fly ash reacts chemically with and absorbs alkalis in the cement, thus making them unavailable for reaction later with the reactive aggregate. One example of fly ashes unique properties to reduce AAR was documented by the State of Alabama in 1960. The Alabama Highway Department specified that Class F fly ash be utilized in all concrete pavement, bridges and culverts. Time-tested results have been positive, according to department representatives. Bridges more that 20 years old have exhibited improved resistance to AAR.

Class F fly ash has been shown to be effective in reducing AAR expansion[7]. Fly ash reacts with CH, alkalis are consumed in the cementitious phase where they are kept from reaction with the aggregate. The curve (figure 2) show concretes with different dosage (0-40 % fly ash) of 3 different fly ashes.

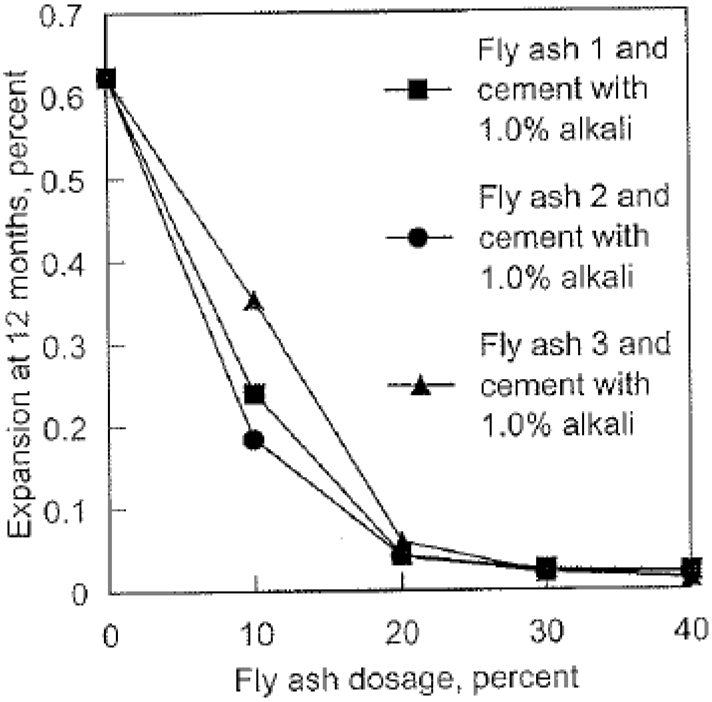

Figure 2. Expansion of concrete mixtures containing alkali silica reactive aggregate and different fly ashes (Note: Fly ash can be used to control AAR. The required dosage is dependent on the fly ash.) Figure copied from ACI Education Bulletin E3[7].

Extensive tests performed at CANMET have shown that the use of high-performance, high-volume fly ash concrete can effectively reduce the expansion due to AAR[8 10]. This has been demonstrated by several accelerated test methods performed on concrete made with known aggregates. They think that the effectiveness of fly ash in reducing expansion due to AAR in high-volume fly ash system is a function of the chemical composition of the fly ash, and in particular their calcium and alkali contents. CANMET results have shown that fly ash with high alkali contents (7-9 % Na_2O equivalent) could possibly be used in the high-volume fly ash system to control AAR in concrete, provided the CaO content of the fly ash is <15 %.

They think the reduction in expansion due to AAR in the high-volume fly ash concrete results from the dilution effect due to the reduced cement content, the low permeability of the concrete, the reduction of the pH of the pore solution by consumption of the CH, and from changes in calcium/silica ratio of the CSH that allows more alkalis to be trapped in the CSH.

Data are present from a number of different research programs on the use of pozzolans and slag to control alkali-silica reaction (ASR/AAR)[12]. The pore solution of pastes, the expansion of mortars bars stored in hot alkaline solution and expansion of concrete stored over water are all strongly influenced by the chemical composition of the cementing material used. The lower the calcium content and higher the silica content of the blended cement, the lower the pH of the pore solution and expansion of mortars and concretes. Consequently, secondary cementitious materials (SCM) with high levels of silica and low level of calcium are likely to be more effective in controlling AAR. The alkali content of the pore solution provides a reasonable indication of the potential for expansion in most cases. But it is possible to have a high pore solution pH and little or no expansion provided the calcium/silica ratio is low enough. Such a case might be when level of high-alkali fly ash is used in concrete.

Relationships based on chemical composition of the blended cement are limited due to their failure to account for the mineralogy. This is particularly true for fly ash, which may contain silica as inert crystalline quartz in addition to the reactive glass phases.

Increasing AAR because of fly ash or increased fly ash content is not registered by any authors in this study.

3.1.10 Sulfate resistance

A comparative study on the sulphate resistance of concrete made with an ASTM Type V cement (high sulphate resisting cement), and with cements incorporating slag or fly ash was commenced at CANMET in 1991[3]. Concrete specimens of similar w/cm after 28 days moist curing were immersed in 5 % Na_2SO_4. The condition after 10 years showed no significant length change. The high volume fly ash concrete visually looked better than the slag and the control concrete. They think this is due to low permeability.

Fly ash reduces sulphate deterioration in three important ways[6]:

- Fly ash chemically binds the CH in calcium silicate hydrate (CSH) rendering it unavailable for sulphate reaction to gypsum (calcium sulphate) and ettringite (calcium sulfoaluminate).
- Fly ash reduced the concrete permeability, keeping sulphate from penetrating concrete.
- By replacing a part of the cement content with fly ash, the amount of reactive aluminates is reduced, and the reaction with sulphate to ettringite is reduced.

In the same bulletin it is mention that United States Bureau of Reclamation (USBR) show that properly proportioned concrete utilizing up to 35 % Class F fly ash will withstand sulphate attack far better than conventional Portland cement. Plain and fly ash concrete mixes using Type I (normal Portland cement), Type II (moderate sulphate resisting and cement with heat) and Type V (high sulphate resisting cement) were tested in sodium sulphate under standardized conditions. In all instances, Class F fly ash concrete was better than conventional Portland cement concrete. The test demonstrated that Type II cement with Class F fly ash was more resistant to sulphate attack than Type V cement alone. The Portland Cement Association (PCA) reports the use of Class F fly ash improves sulphate resistance, while Class C fly ash is less effective and may even accelerate deterioration. They also mention that further United States Bureau of Reclamation (USBR) work correlates the chemistry of a given fly ash with its ability to resist sulphate attack through a mathematical equation called the R-factor formulated below:

$$R = \frac{CaO - 5}{Fe2O3}$$

The limits established by the USBR requiring progressively lower values as sulphate attack severity increases are as follow:

R Limits	Sulfate resistance
<0.75	Greatly improved
0.75-1.5	Moderately improved
1.5-3	No significant change
>3.0	Reduced

ACI reports that fly ash with CaO content less than 15 % will generally improve sulphate resistance[1].

A study made of CANMET on concrete specimens immersed in a 5 % Na_2SO_4 solution for 7 years demonstrated very good performance in sulphate resistance of high-volume fly ash concrete made with ASTM Class F fly ash [8 10]. Duration of moist curing before immersion into Na_2SO_4 was 28 days. The high volume fly ash concrete performed better than the reference concrete with sulphate resisting cement (ASTM Type V) and also better than concrete incorporating 25 and 50 % slag as a partial replacement for cement. It should be noted that the w/cm was different for the different concretes. Nevertheless, the data shows that the performance of the high volume fly ash concrete with w/cm=0.31 is superior to that of other concretes with much higher cement content. The primary reasons for the low expansion appear to be the low permeability and the dilution effect of less CH and aluminate. Most of the CH is consumed in pozzolanic reactions, thus inhibiting the sulphate reaction.

3.1.11 Resistance to penetration of chloride ions

The high-volume fly ash concrete used in the Liu Centre shows very high resistance to the penetration of chloride ions in the tests performed according to ASTM C 1202, and higher resistance than conventional concrete[8].

Concrete with and without Class F fly ash (C35 concrete) has been exposed in a marine tidal zone for 1 and 10 years[11]. The duration and temperature of the moist curing period was found to have little effect on the extent of chloride penetration after age of 1 year. The resistance to chloride penetration increases significantly as the fly ash content of the concrete increases. Three different grades of concrete (C25, 35 and 45) show that the lower C25 (w/cm=0.44) concrete with 50 % fly ash shows far better performance to the higher strength C45 (w/cm=0.49) concrete without fly ash (figure 3).

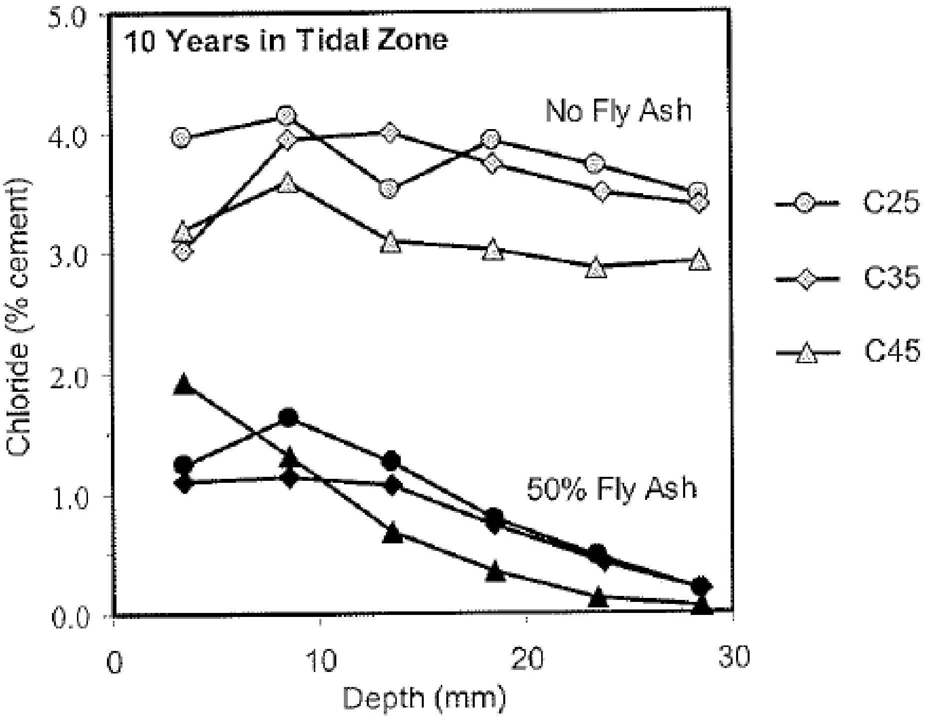

Figure 3. Effect of strength on Chloride penetration after 10 year. Copied from Thomas et al.[11]

Bouzoubaâ et al. have made concretes using high-volume fly ash blended cements (55 % Class F fly ash) and concrete in which the same fly ash had been added as a separate material at the mixer[9]. Two fly ashes were tested, one coarse and one finer. Two cements were also tested, a commercially available ASTM type III cement and a laboratory made normal Portland cement. Blaine of the fly ash was respectively 196 and 306 m^2/ kg. The blended cement had a blaine of about 550 m^2/kg. The resistance to chloride ion penetration was significantly higher for the concrete incorporating fly ash than for the control concretes without fly ash. Further, the concrete made with blended cements showed higher resistance than the concretes in which the fly ash had been added at the mixer.

3.1.12 Corrosion of steel reinforcement

Laboratory tests have shown that high-volume fly ash concrete can provide an excellent protection to the reinforcing steel against corrosion[8]. After 6 months in a 3.4 % sodium chloride solution, there was no significant corrosion in the concrete with only 13 mm of concrete cover. The high-volume fly ash concrete was better than a ordinary concrete without fly ash, and equivalent to that of a high-performance Portland cement concrete with w/c=0.32 and 376 kg/m^3 cement.

Because the permeability of the fly ash concrete is reduced, the ingress of chlorides into the concrete will also be reduced and onset of the corrosion may be delayed[7].

3.1.13 Freeze-Thaw

Freeze-thaw deterioration begins when water enters voids in concrete[6]. When freezing, the water expands 9 % in volume and generates a pressure of 30,000 psi. To combat this entrained air void have been found useful in resisting freeze-thaw cycles, because the small air voids acts as a pressure release vessel. ACI recommends proper amount of suitably sized and spaced air bubbles into the concrete, minimum level of compressive pressure, proportion the mix for low concrete absorption, high density and low permeability and properly curing before exposure to freeze-thaw.

High quality fly ash will help achieving several of these recommendations:

- Fly ash reacts with CH to CSH, thereby reducing the amount of CH that may be leached out of the concrete. Leaching of the CH increases concrete voids which can accelerate freeze-thaw damage.
- Fly ash fills in the small voids, creating a denser and less absorptive concrete.
- Fly ash reduces the amount of water required in the mix because of the spherical shape, and this reduces the bleed channels and entrance of water.
- Fly ash helps maintain an even distribution of entrained air through the plasticizing effect that fly ash particles have on concrete mix.
- Fly ash helps produce higher compressive strengths long term that provide a strong concrete which resists the forces generated during the freezing of water in the voids
- Fly ash concrete is more stable, uniform, dense, less absorptive and less permeable, all factors which improve freeze-thaw durability.

A properly air-entrained high volume fly ash concrete (Class F fly ash) has excellent resistance to repeated cycles of freezing and thawing in the ASTM C666 test (freezing and thawing in water)[3]. In the investigation, even after 1000 cycles the durability factors were excess of 90; conventional air-entrained Portland cement concrete is considered satisfactory if it can withstand 300 cycles. The resistance to freezing and thawing cycles is a direct function of the air entrainment and hence the air void parameters of concrete, and not the amount of type of fly ash in it.

Concretes have been made using high-volume fly ash blended cements (55 % Class F fly ash) and concrete in which the same fly ash had been added as a separate material at the mixer[9]. The Blaine of the fly ash was 306 m^2/ kg. The laboratory blended cement was ground to a Blaine of 450 m^2/ kg. All the concretes show good resistance to freezing and thawing after 300 cycles. The residual flexural strength of the prisms also demonstrated excellent performance of the concretes with values ranging from 73.2 to 94.5 % of the reference prisms which were placed in moist curing room.

3.1.14 De-icing salt scaling test

The high-volume fly ash concrete used in the Liu Centre showed poor performance in the de-icing salt scaling test done at CANMET using ASTM C 672, but other investigators using other materials and mixture proportions, have shown that high-volume fly ash concrete can perform adequately in the de-icing salts scaling test[3 8 10]. Also sidewalk sections made with this concrete in 1994, and subjected to de-icing salts, have shown good performance since construction.

A 15-year old high volume fly ash concrete pavement in Wisconsin and 9-year old sidewalk sections made in Halifax with same type of concrete both exposed to de-icing salts has shown good performance[3].

Trial sections of two sidewalks have been constructed in Nova Scotia of a 35 MPa concrete with 390 kg/m^{3}cement and 55 % Class F fly ash[13]. They concluded: With the respect of salt scaling, the high-volume fly ash concrete performed better in the field than that would be predicted by laboratory tests. This is confirmed by the field demonstration projects.

3.1.15 Strength

In conventional concrete the flexural strength reaches a maximum value between 14 and 28 days[3]. In high volume fly ash concrete the strength keeps on increasing with age because of the pozzolanic reaction of fly ash, and strengthening of the interfacial bond between cement paste and aggregate.

Due to slow pozzolanic reaction, the compressive strength at later ages of high volume fly ash concrete will be general good[8]. The properties are strongly dependent on the characteristics of the cement and fly ash used. The ratios of the flexural and splitting-tensile strengths to compressive strength are comparable to the conventional concrete.

Concrete cores taken from a large experimental blocks made from ready-mixed high volume fly ash concrete have shown a compressive strength of 110 MPa after 10 years in outdoors exposure[10]. This demonstrates a potential for long-term strength gain in this type of concrete.

Concretes have been made using high-volume fly ash blended cements (55 % Class F fly ash), one coarse and one finer fly ash and concrete in which the same fly ash had been added as a separate material at the mixer[9]. The blaine of the fly ash was respectively 196 and 306 m^2/ kg. The strength development of the concrete made with blended cements was faster up to 28 days than that of the concrete in which unground fly ash was added at the concrete mixer. The improvement when grinding the fly ash with the cement is more significant for the fly ash which has the lowest blaine.

3.1.16 Curing

The curing of a high volume fly ash concrete is important[8 10]. It is most essential that this concrete be protected from premature drying by curing for adequate length of time. In general a curing time of 7 days should be adequate.

The 28 days strength is quite equal between concrete with 50 % Class F fly ash and concrete with no fly ash when moist cured in 20°C at 3 days or more (concrete with estimated strength 25 and 45 MPa at 28 days)[11]. When moist cured for 1 day the concrete with 50 % fly ash got a lower strength than the ordinary concrete.

For specimens cured at 20°C the permeability of Class F fly ash concrete (50 % fly ash) was lower than for equivalent grade concrete with no fly ash[11]. The improvements attributed to the fly ash become more significant as the moist curing period increased and as the strength grade of the concrete increased. When the curing temperature was reduced to 5°C the permeability of the fly ash concrete was observed to increase and there where little difference between the fly ash and control concrete. The permeability of the fly ash concrete is clearly more sensitive to the duration of the moist curing period when curing at lower temperatures.

3.1.17 Carbonation

Carbonation is generally tested by an indirect method using phenolphthalein 3. A solution of phenolphthalein indicator is applied onto a fresh cut concrete surface. The indicator changes the colour at pH about 9. The uncorbonated concrete with pH > 9 gets a violet colour, while the carbonated concrete with a lower pH remain grey. This test method cannot be used to determine the rate of carbonation in a high volume fly ash concrete because, with age, most or all of the CH in this type of concrete is removed by the pozzolanic reaction involving high volumes of fly ash, and not by the carbonation. Using direct tests for carbonation, well-cured high volume fly ash concretes, due to this low permeability and high crack resistance, are not expected to show any significant carbonation. The low permeability and high electrical resistivity would be the major factors in reducing the potential for reinforcement corrosion in high volume fly ash concrete structures.

The high volume fly ash concrete block cast at CANMET has shown 11.5 mm carbonation after 13 years[14]. The concrete block was moist cured for 28 days, and then left in a room with limited ventilation, a temperature of about 23°C and 40-50 % RH. If the carbonation is proportional to the square root of time, the depth of carbonation for this concrete under this condition would be of the order of only 35 mm after 100 years of exposure. Other data on carbonation of high-volume fly ash concrete exposed for 10 years to outdoor conditions in Ontario, Canada, have shown negligible carbonation depths of 3-5 mm.

3.1.18 Colour

As fly ash consumes the excess lime there is a reduced risk of efflorescence from the concrete[15].

3.1.19 Leachability

The leachability of trace elements (Ag, As, B, Ba, Cd, Cr, Cu, Hg, Pb, and Se) from 9 fly ashes from Canada and USA were tested, seven of them were Class F fly ash, both in the fly ash and in the concrete[20]. The fly ash content reached from 10 to 60 % of the total cementitious materials. The w/cm of the concretes ranged from 0.40 to 0.70. For various leaching test, three different curing regimes were used in the study (1 day, 7 days and 28 days moist curing). The leaching test called EPA TCLP test was used in the study (18-hr extraction). Regardless of type and content of the fly ash used, w/cm of the concrete, and curing condition, none of the trace metals in the leachates from the fly ash concrete samples exceeded the regulated concentration limits by the United States Environment Protection Agency and the Transportation of Dangerous Goods Act regulations of Canada. The concrete incorporating fly ash, therefore, considered environmentally stable.

3.2 Disadvantages

3.2.1 Air Content

In general, there is no difficulty in entraining air in high volume fly ash concrete[3]. 5-7 % air can be routinely incorporated into high volume fly ash concrete mixtures. However, occasionally one may run into difficulty when the carbon content of the fly ash being used is high (> 4 %) or when activated carbon particles are present.

The carbon content affects the air entraining agents and reduces the entrained air for a given amount of air-entraining agent[2]. The carbon will absorb water. An additional amount of air-entraining agent will need to be added to get the desired air content.

Some fine fly ash results in a higher water demand due to increase in surface area. But this is not always as mention above under the chapter 3.1 Advantages. The finer fly ash requires more air-entraining agent to give the mix the desired air content.

If a fly ash contains an appreciable amount of carbon, it may be difficult to control the air content[7].

3.2.2 Slump

Because of the very low water content the slump of high volume fly ash concrete is low, and therefore, it is essential to use a superplasticizer when a high slump is needed for placement[3]. This does not need to be a disadvantage.

3.2.3 Setting time

NS-EN 450-1 demands the initial setting time not to be more than 120 minutes longer when the fly ash is tested. When the fly ash is ground together with the clinker the setting time of the composite cement is improved and regulated with the fineness and the gypsum content.

Cold weather can have detrimental effects on concrete construction unless adjustments are made and precautions are taken to ensure acceptable performance[1]. The ACI defines cold weather as any time three consecutive days exhibit average daily temperature less than 40°F (4.4 °C). Both conventional and fly ash concrete that performs well at normal temperatures may perform unacceptably in cold condition because of the decreased rate of hydration. If the concrete mix is adjusted, it is possible to reach the setting and strength gain required.

The setting time for the high volume fly ash concrete at Liu Centre was in general somewhat longer than for a conventional concrete[8].

High volume fly ash concrete hydrates more slowly than an ordinary concrete[16]. This factor, which increases with increasing fly ash replacement dosage, presents a problem in concrete construction where rapid stripping and turnaround are essential.

3.2.4 Curing and permeability

Concrete with 50 % Class F fly ash and moist cured in 5°C for 1, 3 or 7 days got lower 28 days strength than concrete with no fly ash[11].

When the curing temperature was reduced to 5°C the permeability of the fly ash concrete was observed to increase and there where little difference between the fly ash and control concrete[9]. The permeability of the fly ash concrete is clearly more sensitive to the duration of the moist curing period when curing at lower temperatures. They concluded with that high volume fly ash concrete is more sensitive to duration of moist curing than Portland cement concrete, especially at low ambient temperatures.

3.2.5 Deicing salt scaling resistance

The high-volume fly ash concrete used in the Liu Centre showed poor performance in the de-icing salt scaling test done at CANMET using ASTM C 672[3 8 10]. During this test, both visual examination and weight loss of the test specimens indicated severe scaling. According to the ASTM scale of visual rating of 0 to 5, the test specimens were rated to 5. The control plane Portland cement concrete made with the same w/cm and the same cementitious materials content has shown good scaling resistance and a rating of 1. As mentioned under section advantages other investigators using other materials and mixture proportions, have shown that high volume fly ash concrete can perform adequately in the de-icing salts scaling test.

Several laboratory and field investigations involving cements and fly ash from various sources in Canada and USA have demonstrated excellent durability of high volume fly ash concrete, the only exception being deicing salt scaling resistance[8].

Fourteen air-entrained concrete mixtures were made before 50 cycles of freezing and thawing in a 3 % NaCl solution (ASTM C 672)[17]. W/cm of the concrete ranged from 0.32 to 0.45. Three fly ashes, two with Class F and one with Class C, were included in this investigation, and the fly ash content ranged from 25 to 58 %. They were compared with two control Portland cement concrete with w/cm of 0.40 and 0.45. The type and the amount of fly ash and w/cm affect the de-icing salt scaling resistance. In general, the resistance decreased with increased amounts of fly ash and for some with increased w/cm.

When cured with a curing compounds, both the control concrete and the fly ash concrete, showed less scaling than the concrete cured in moist room. One of the three fly ashes (Class F) performed worse than the other. The poor performance is probably due to its coarse particle size, higher loss of ignition and poor pozzolanic activity.

Seven air-entrained concrete mixtures with 25, 35 and 58 % Class F fly ash were made in this laboratory study[18]. W/cm ranges from 0.32 to 0.45. The fly ash concrete showed more de-icing salt scaling compared to the ordinary concrete with same w/cm. However, concretes with up to 35 % fly ash and a w/cm $\leq$ 0.40 performed well in the test. Use of curing compound greatly improved the scaling resistance of all concretes tested but was more beneficial for the fly ash concrete.

Norcem R&D has tested several concretes both in the laboratory and in the field. The results of the tests demonstrate very good performance despite of dubious laboratory results. The conflicting results are attributed to the tests precuring conditions as well as certain aspect of the laboratory testing procedure with slow developing binders.

Bouzoubaâ et al made concretes using high-volume fly ash blended cements (55 % Class F fly ash) and concrete in which the same fly ash had been added as a separate material at the mixer[9]. Two fly ashes were tested, one coarse and one finer. Two cements were also tested, a commercially available ASTM type III cement and a laboratory made normal Portland cement. Blaine of the fly ash was respectively 196 and 306 m^2/ kg. The laboratory blended cement was ground to a Blaine of 450 m^2/ kg, same as the type III cement. Reference concretes without fly ash were also made. The concrete with fly ash show poorer resistance to de-icing salt scaling than the reference concrete without fly ash. In-spite of the excellent mechanical properties and durability characteristics, the concrete with fly ash blended cement show the poorest performance due to de-icing salt scaling resistance, and poorer than the concrete in which fly ash had been added as a separately material at the mixer. The reasons for this are unexplained.

3.2.6 Carbonation

Carbonation in concrete usually is tested by the indirect method using phenolphthalein described in chapter 3.1 Advantages. This test method cannot be used to determine the rate of carbonation in a high volume fly ash concrete because, with age, most or all of the CH in this type of concrete is removed by the pozzolanic reaction involving high volumes of fly ash, and not by the carbonation[3]. Even if using direct tests for carbonation, well-cured high volume fly ash concretes, due to the low permeability and high crack resistance, are not expected to show any significant carbonation. The low permeability and high electrical resistivity would be the major factors in reducing the potential for reinforcement corrosion in high volume fly ash concrete structures

Concretes with Class F fly ash were stored outdoors with protection from direct precipitation[10]. This exposure condition is felt to be the most relevant for predicting the service life of reinforced concretes subjected to carbonation-induced corrosion. Tests at BRE indicate that C25 concrete with 50 % fly ash carbonates 20 mm after 4 years in this outdoors exposure. The concrete containing 50 % fly ash carbonates at a significantly faster rate than the concrete with no fly ash, and that the difference in performance is more marked in poorly cured concretes of low strength grade. Lower temperature curing does not exacerbate the differences between the fly ash concrete and the control concrete. They concluded with that poorly cured, low strength concrete (e.g. 25 MPa) with high levels of fly ash may carbonate rapidly.

3.2.7 Cracking and shrinkage

The paper discusses the effect of fly ash on cracking tendency during the hardening phase due to external restraint[19]. The study was conducted with a constant water-to-binder ratio (w/b) of 0.40 and with an efficiency factor for FA of 1.0. The results show that the concrete with 35 % fly ash of binder has 25 % lower cracking tendency than the reference concrete with ordinary Portland cement. Any practical relevant mix-design with fly ash added directly during the mixing process should be done with an efficiency factor of 0.4 according to NS-EN 206-1. This leads to a higher binder content, more hydration heat and more autogenous shrinkage than measured for the tested fly ash concrete. The efficiency factor is 1.0 for fly ash and slag if the materials are a part of a certified cement (cement type CEM II and III). For cracking tendency it appears more favourable to use CEM II and III cements than using the same amount of fly ash or slag added separately during concrete mixing.

3.3 Field experience

Due to differences in the curing temperature and humidity, the actual strength of concrete in a structure will not be the same as the strength of laboratory or even a field-cured cylinder[3]. The author show examples of test cores taken from real and mock-up of structural elements, that showed a higher early strength of high volume fly ash concrete in structure than in laboratory.

The author lists several field projects with high volume fly ash concrete with Class F fly ash:

- Concrete block communication satellites, Ottawa Canada 1987: After 15 years, the blocks are performing satisfactory for the intended purpose.
- Park Lane Hotel, Halifax Canada 1988: There were no unexpected problems with the concrete, and the cost was lower compared to a conventional Portland cement concrete.
- Purdy's Wharf Development, Halifax Canada 1990: Satisfactory.
- Polypropylene fibre reinforced high volume fly ash shotcrete, Halifax International Airport Canada: The experimental sections show satisfactory performance after about 100 cycles of freezing and thawing per year. Built in 1992?
- Artists Live/ Work studios, Vancouver Canada 2001: The architect wanted to have a concrete with lighter colour and high quality surface finish. According to the contractor, the concrete produced was of good quality with attractive finish.
- Wurster Hall University of California, Berkeley USA 2001: The concrete was chosen because it costs was less than conventional concrete.
- Seismic rehabilitation of Barker Hall University of California, Berkeley USA 2001: After the successful completion of the project, the project team concurred with a list of positive observations.
- Hind Temple, Hawaii USA 1999-2002: The construction was built to last at least a thousand years. The concrete mixture selected needed to keep thermal and drying shrinkage stresses to an absolute minimum. After 2 years no cracking is shown. A petrographic examination showed good quality of the concrete and little or no microcracking.
- Residential Building in San Francisco 1999-2004: Crack-free concrete to low cost.
- High volume fly ash concrete pavements in India 2002-2004: The concrete was mixed on site using a concrete tilting mixer, and all the concrete operations were done by manual labour. After 2 years of operation under heavy vehicular traffic the pavement is working satisfactory, but with some minor surface scaling on parts of the pavement.

High-volume fly ash concrete prisms 305x305x915 mm have been exposed to marine environment at Treat Island, Maine since 1987[8]. They are exposed both to the marine atmosphere and the immersion in sea water. Therefore, the prism are exposed to a combination of wetting and drying cycles, chemical attack, and >100 cycles of freezing and thawing in the presence of salts during the winter. After 9 years of exposure the high-volume fly ash concrete prisms with water to cementitious materials of 0.31 are in excellent condition. The concrete with w/cm of 0.35 show surface scaling. Based on laboratory experience, it is recommended for this type of exposure a w/cm of $\leq$ 0.32.

Thomas et al. mentions in an article that the use of high levels of fly ash has generally been restricted to special applications such as roller-compacted concretes and large monolithic pours requiring temperature control[11]. But high volume fly ash concrete (40-60 %) can be successfully used in normal structural concrete.

3.4 Coarse / fine fly ash

Norcem and Lehigh, two cement producers in Heidelberg Cement North Europe, have long experience with intergrounding of fly ash and clinker to produce cement. Both have found improved properties. The fly ash cement (Norcem Standard fly ash CEM II A/V) is produced by adding fly ash to the mill inlet or to the mill separator. In both cases the coarse particles will be separated back into the mill until they are fine enough. This gives a finer and more reactive fly ash than the fly ash added directly into the concrete mixer.

In this study an original and ground fly ash were tested according to mortar bar pozzolanic activity with lime and Portland cement (ASTM C 311)[14]. The fly ash/lime activity index was lower than referred value in ASTM C 618, but the ground sample gave higher activity index than the original. The ground fly ash showed an increase in compressive strength.
When tested the fly ash with Portland cement the value exceed the limits of the ASTM C 618 (75 %). The ground fly ash has a higher activity index than the original fly ash.

C. Jaturapitakkul et al investigated the strength activity index of ground coarse fly ash and fine fly ash[21]. Four different fly ashes replaced cement 20 % by weight to make mortars. They find out that strength activity index of coarse fly ash can be improved by grinding. The chemical composition did not change much of the different particle size. For a good quality of fly ash, either by classifying or grinding, the important factor is fineness, but also shape of the particles. Fly ash with small particle size increased strength and the strength gain. They also experienced that to keep the same workability of mortar, the fine fly ash demanded less water than the coarse one.

Chindaprasirt et al. studied the effect of fly ash fineness on the compressive strength of concrete[22]. Three fly ash finenesses (100 % original coarse fly ash, medium fine with 45 % of original fly ash, fine with 10 % of the original fly ash), fly ash dosage of 30 % of binder in three concrete mixes, low, medium and high strength concrete, the strength was measured up to 90 days. They find out that the strength of fly ash concrete were higher than those of the Portland cement concrete in the same group. The reduction of the water content, the good dispersing and filling effect of the fly ash contribute to the good strength development of the fly ash concrete. With use of finer fly ash, the water content was further reduced and strength of concrete enhanced further.

In another paper Chindaprasirt et al. had found out that the glass content of the fine fly ash portion is higher than of the coarser fly ash portion from the same batch[23].

Chindaprasirt et al. have also investigated the influence of fly ash fineness on strength, drying shrinkage and sulphate resistance of blended cement mortars[24]. In addition to original fly ash, five different fineness values of fly ash were obtained by sieving and using an air separator. They found out that fine fly ash gave increased strength because of the packing effect and reduced water demand. The coarse fly ash, lacking both the medium and fine fraction, increased the water demand owing to the rougher surface of the coarser particles. The drying shrinkage was reduced for all of the mortars with fly ash. The fine fly ash has reduced expansion of the mortar bars immersed in the sodium sulphate solution. This was due to reduced w/b compared with the coarse fly ash mortars with higher w/b.

Erdogdu and Tűrker found that sieved fine fly ash increased the strength of mortar samples compared to that of the mortar made from the original coarser fly ash. They also found out that the chemical composition did not vary from the fine to the coarse fraction of the investigated Class F fly ash.[25]

As mention above Bouzoubaâ et al made concretes using high-volume fly ash blended cements (55 % Class F fly ash) and concrete in which the same fly ash had been added as a separate material at the mixer[9]. Two fly ashes were tested, one coarse and one finer. Two cements were also tested, a commercially available ASTM type III cement and a laboratory made normal Portland cement. Blaine of the fly ash was respectively 196 and 306 m^2/ kg. The blended cement had a blaine of about 550 m^2/kg. The coarse fly ash that fails to meet the fineness requirements of ASTM C618 had been used successfully to produce high volume fly ash blended cement. The mechanical and durability properties of concrete made with this blended cement, was comparable with the finer fly ash blended cement. The production of blended cements offers a possible way for the utilization of coarse fly ashes.

The concrete with fly ash show poorer resistance to de-icing salt scaling than the reference concrete without fly ash. In-spite of the excellent mechanical properties and durability characteristics, the concrete with fly ash blended cement show the poorest performance due to de-icing salt scaling resistance, and poorer than the concrete in which unground fly ash had been added as a separately material at the mixer. The reasons for this are unexplained.

4 Discussion

In this study it has been focused on literature of the use of ASTM Class F fly ash in concrete as a part of blended cement or used directly into concrete mixer. Reported advantages, disadvantages and field experience have been collected. Several search on the Web for literature has been done, and a lot of articles and referrals have been checked, some with field results, but most of them with laboratory results.

There were many articles that highlight the good properties of the use of fly ash, but few with the connection between fly ash blended cements and fly ash blended concretes and field constructions.

The advantages of the fly ash concrete can be listed up as following:

- Environmental friendliness with respect to CO_2 emission and energy saving due to less production of energy-intensive cement and less landfills.
- Better workability due to fly ash fineness, particle effect and the spherical particle shape with lubricating effect.
- Less bleeding due to less water demand and greater volume of fines.
- High ultimate strength due to the pozzolanic reaction that produce more CSH.
- Better crack resistance due to denser paste because of more CSH.
- Better resistance to penetration of chloride ions due to denser paste.
- Better electrical resistivity due to denser paste.
- Higher durability due to denser paste, less CH and consumption of alkali in the CSH.
- Lower heat of hydration due to lower amount of hydrating cement and slow pozzolanic reaction.
- Low permeability due to denser paste.

The good performance of fly ash concrete due to alkali aggregate reaction is well documented. In North America it is well accepted practice to use pozzolanic admixtures to control AAR. The California Department of Transportation requires an amount of at least 25 % of the cementitious material in all concrete used for the construction of state-funded highway project. Studies at CANMET have shown that, with high volume alkali Portland cement and reactive aggregate, the use of high volume fly ash concrete can effectively reduce the expansion due to AAR. The reduction in expansion results from low permeability, alkali-dilution effect due to the reduced cement content, the reduction in the pH of the pore fluid due to the pozzolanic reaction, and a change in composition of CSH which allows more alkalis to be trapped in the CSH structure. A good example of fly ashes unique properties to reduce AAR was documented by the State of Alabama in 1960. The Alabama Highway Department specified that Class F fly ash be utilized in all concrete pavement, bridges and culverts. Time-tested results have been positive, according to department representatives. Bridges more that 20 years old have exhibited improved resistance to AAR. Increasing AAR because of fly ash or increased fly ash content is not registered by any authors in this literature study.

Even if the use of fly ash has a lot of advantages there always will be events of less favourable experience. The variation of cement types, fly ashes, admixtures, aggregates, environment and temperature are great. Good results of a concrete mix in one country can be worse with other materials in another area.

Malhotra and Metha[3] pointed out in their article that there is no difficulty in entraining air up to 5-7 % in high volume fly ash concrete. Occasionally some one may have problems when the carbon content of fly ash is high (> 4 %). This might be due to carbons ability to absorb air entraining agent and water. Higher amount of agent has to be used.

The main drawback with high volume fly ash is a slower strength development. This makes a problem in concrete construction where rapid stripping and turnaround are essential[16.] The reason is a smaller amount of cement to hydrate. The pozzolanic reaction of the fly ash is slow, but contributes to the later strength. To increase the strength of high volume fly ash more reactive cement or finer fly ash may be used. Another possible solution is to change the demand for 28 days strength to 90 days.

Both conventional and fly ash concrete that perform well at normal temperatures may perform unacceptably in cold weather due to decreased rate of hydration[1]. Concrete mix adjustments and precautions have to be performed when low temperatures occur (< 4.4°C according to ACI). Other investigators have experienced that moist curing at 5°C leads to lower strength and more permeable fly ash concrete. They concluded with that high volume fly ash concrete is more sensitive to duration of moist curing than Portland cement concrete, especially at low temperatures.

Another problem occurring when high fly ash concretes are tested is de-icing salt scaling. The fly ash concrete acts well in the freeze thaw test, but when the de-icing salt scaling is performed, some fly ash concretes show more scaling than ordinary concretes. Zhang, Bilodeau, Shen and Malhotra[17] have tested 3 different fly ashes (two Class F and one Class C). They found out that the resistance to de-icing salt scaling decreased with increased amount of fly ash and for some with increased w/cm. They could not explain why the resistance decreased with increased w/cm for some of the concretes. Perhaps this is due to more porous paste with space for the reaction product. The phenomenon may also be attributed to the slower structural and mechanical properties development in fly ash concrete.

However, there is always a question about the quality of the method used in the tests. Therefore this study intended to focus on field experience. There are examples of good high volume fly ash concrete. A 15-year old pavement and 9-year old sidewalk section with same high volume fly ash concrete both exposed to de-icing salts have performed well since. In another project trial sections of two sidewalks with 55 % fly ash concrete have been constructed. The concrete in field performed better than predicted by the laboratory tests.

Several other successful field constructions with high volume Class F fly ash concrete are mentioned by Malhotra and Metha[3]. The exact concrete mixes are unfortunately not described.

The investigation showed that poorly cured high volume fly ash concrete of low quality grade C25 carbonated more rapidly than ordinary concrete[10]. This might be due to the porous microstructure of the low grade concrete. Some other investigations show little carbonation due to well-cured fly ash concretes with low permeability[3 14].

When the Canadian talk about high volume fly ash concrete they think about 50-55 % fly ash and often fly ash directly into the concrete mixer. In Norway some concrete producers use fly ash in same way, but with less fly ash amount. However most of the fly ash is used through the fly ash blended cement CEM II A/V from Norcem with 20 % Class F fly ash. The advantage with the blended cement is a finer fly ash due to grinding of the clinker and the fly ash. Finer particles are more reactive due to increased surface area. Bouzoubaâ et al.[9] investigates fly ash blended cement and concrete which fly ash had been added as a separate material at the mixer. They concluded that the coarse fly ash had been used successfully to produce fly ash blended cement with good mechanical and durability properties of the concrete, comparable with the finer fly ash blended cement.

But also an original fine fly ash may be more reactive than a coarser one. Chindaprasirt et al.[23] had found out that there is a higher glass content in the small than in the coarse fly ash particles. Another study showed that the activity index is higher for the ground than for the unground fly ash[14]. Also Jaturapitakkul et al.[21] have investigated four different fly ashes due to strength activity index and found out that grinding increased the index value.

The literature describes a few test in terms of fine and coarse fly ash, fly ash blended cement and blended concrete. Some of them have performed the test on mortars and not concrete. Erdogdu and Tűrker[25] show that sieved fly ash mortars gave increased strength compared to mortars with the original coarser fly ash. Chindaprasirt et al.[22] tested concrete with three different fineness and references without fly ash. They found out that concrete with fly ash have higher strength at 90 days due to reduction of the water content, good dispersing an filling effect of the fly ash. Finer fly ash gave even better strength.

The literature above shows that the fly ash properties are dependent of the fineness of the particles. Factors as content of carbon, glass phase and shape of the particles is also important. The requirements to the ASTM Class F / EN 197-1 Type V contribute to a fly ash of good quality including fineness at least 66 % < 45 µm. Even some reports poor behaviour of some fly ash concrete in laboratory test, there are few examples of poor field construction with fly ash concrete. Perhaps this is because of its good properties, or the reason is no one wants to report failed projects.

5 Conclusion

In this literature study it has been focused of the use of ASTM Class F fly ash in concrete, as a part of blended cement or used directly into concrete mixer. There were many articles that highlight the good properties of the use of fly ash, but few with the connection between fly ash blended cement and fly ash blended concrete and field construction.

Several successful field constructions with high volume Class F fly ash concrete are mentioned by Malhotra and Metha. One of the important advantages with fly ash concrete is the resistance to alkali aggregate reaction (AAR). The good performance of fly ash concrete due to AAR is well documented. Increasing AAR because of fly ash or increased fly ash content is not registered by any authors in this literature study.

The fineness seems to be important for the pozzolanic properties of the fly ash. An advantage with fly ash blended cement as CEM II A/V is a finer fly ash due to grinding of clinker and fly ash. But use of fine ASTM Class F / EN 197-1 Type V direct into the concrete should be possible.

Even if the use of fly ash has a lot of advantages there always will be events of less favourable experience, because of the test method used, different cement types, fly ashes, admixtures, aggregates, environment and temperature.

The main problems with high volume fly ash concrete seem to be:

- Air entraining because of high carbon content
- Lower early strength because of the slow pozzolanic reaction and less reactive cement content. To increase the strength of high volume fly ash more reactive cement or finer fly ash may be used. A possible solution is changing the demand for 28 days strength to 90 days.
- Poor correlation between de-icing salt scaling test in laboratory and real concrete performance.

Even some reports poor behaviour of some fly ash concrete in laboratory test, there are few examples of poor field construction with fly ash concrete. Perhaps this is because of its good properties of the fly ash concrete used in the construction, or the reason is no one wants to report failed projects.

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Class C fly ash Pleasant Prairi: Sp.gravity 2.6, 33.9 % SiO_2 , 28.2 % CaO, 2.1 % alk, blaine 422 m^2/kg, LOI 0.3. , 80.0 % passing 45 µm.
Class F fly ash Montour: Sp.gravity 2.3, 49.5 % SiO_2, 1.4 % CaO, 1,8 % alk, blaine 241 m^2/kg, LOI 3.7, 66.8 % passing 45µm.)

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